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14. ABSTRACT The objective of this research is to develop new models for predicting the risk of post-traumatic osteoarthritis (PTOA) following intra-articular fracture (IAF). We have analyzed pre- and post-treatment CT data from patients with combat-related IAFs to measure fracture severity and post-reduction contact stress exposure. Our partner at SAMMC finalized enrollment during this year. The imaging data for 70 subjects with collectively 112 fractures have been forwarded to us for analysis, and we have completed fracture severity analysis of 93 IAFs. This is in addition to fracture energies having now been computed for 226 civilian IAFs. In our most recent analyses, we found a strong positive correlation (explaining ~85% of the variance) between fracture energy per unit contact area and PTOA rates across 5 different joints, without controlling for any operative factors, whatsoever. Analyses of contact stress elevation after acetabular IAF demonstrated a clear exposure threshold above which cases predictably progress to PTOA. Using a 2 MPa-s/gait cycle threshold to predict which cases progressed to OA yielded a sensitivity of 100% and a specificity of 83.3%. During the coming no cost extension year, we will be performing further analysis of fracture severity and contact stress to more definitively test these findings prior to reporting them in a series of journal articles.									
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1. Introduction

The objective of this research is to develop new models for predicting the risk of post-traumatic osteoarthritis (PTOA) following intra-articular fracture (IAF). We previously developed capabilities to predict PTOA risk from acute fracture severity (measured from pre-op CT) and chronic elevated contact stress (post-op CT) associated with IAFs, but more patient data are needed to make the risk models clinically useful. Prospective studies of PTOA development following IAFs face many challenges. Severe IAFs are not frequently seen in civilian practice, making it difficult to accrue sufficient numbers for clinical study. An added challenge is that to determine if a patient develops PTOA, they may need to be followed for years into the future, threatening subject retention. One of the attractive features of the CT-based measures of mechanical factors pioneered by the Initiating PI is that retrospective studies can include patients who were injured years in the past. Recent military conflicts, which unfortunately produced a substantial number of IAFs (as reported by the Partnering PI), provide a unique opportunity to overcome these challenges and to honor the military personnel who suffered combat-related IAFs. Given their prevalence and severity, and the degree to which these injuries impact long-term function of injured service members, better methods to predict PTOA risk would benefit our current generation of new veterans, as well as future service members at risk for IAF.

2. Keywords

post-traumatic osteoarthritis, CT analysis, intra-articular fractures, clinical outcome

3. Accomplishments

What are the major goals of the project?

Below is the original SOW:

Specific Aim 1: Evaluate pre- and post-treatment CT data from patients with combat-related IAFs to measure fracture severity and post-reduction contact stress exposure	
Major Task 1: Regulatory Approval	Months
Subtask 1.1: Obtain local IRB	1-3
Subtask 1.2: Obtain HRPO approval	4-6
<i>Milestone #1: Regulatory approval received</i>	5-6
Major Task 2: Adapt CT Analysis Methods	Months
Subtask 2.1: Obtain representative CT studies	3
Subtask 2.2: Trial analysis methods with CT studies	1-3
Subtask 2.3: Modify analysis methods as needed	3-9
<i>Milestone #2: Co-author manuscript on methods to analyze combat-related IAFs</i>	9-12
Major Task 3: Subject Identification	Months
Subtask 3.1: Obtain potential subject list with demographic and injury data from DoDTR	7
Subtask 3.2: Screen available CT scans for requisite images for inclusion	8-12
<i>Milestone #3: Subject list finalized</i>	12
Major Task 4: CT Calculations	Months
Subtask 4.1: De-identified CDs compiled and express mailed from Site 2 to Site 1	9-13
Subtask 4.2: CT calculations for injury severity and post-reduction contact stresses	10-18
<i>Milestone #4: Co-author manuscript on fracture severity and post-reduction contact stress measures in patients with combat-related IAFs</i>	18-24

Specific Aim 2: Measure the occurrence of PTOA up to ten years following fracture reduction surgery	
Major Task 5: PTOA radiographic frequency	Months
Subtask 5.1: Identify radiographs for KL grading; multiple investigators do KL grading	9-14
<i>Milestone #5: Co-author paper detailing PTOA incidence and grading for patients with combat-related IAFs</i>	16-20

Specific Aim 3: Quantify the extent to which fracture severity and post-reduction contact stress predict PTOA	
Major Task 6: PTOA symptoms and quality of life	Months
Subtask 6.1: Identify subjects' contact information through DoD and/or VA sources	12-16
Subtask 6.2: Conduct prospective contacting of subjects for outcomes questionnaires	12-28
<i>Milestone #6: Co-author manuscript detailing symptoms and treatment timelines for patients with combat-related IAFs</i>	25-32
Subtask 6.3: Correlate CT-based analysis results with KL grade/PTOA status, questionnaire outcomes, and various radiographic results	28-32
<i>Milestone #7: Co-author manuscript detailing relationships between CT-based results and PTOA outcomes – PTOA risk model</i>	32-36

What was accomplished under these goals?

Major Task 1 (regulatory approval) completed 23-Oct-2015 (HRPO Log Number A-18855)

Major Task 2 (adapt CT analysis methods) was completed in late 2016, and a manuscript detailing the new methods (see Appendix) has been submitted. The new methods were first detailed in our revised 2016 Annual Report that was submitted on 01-Mar-2017.

Major Task 3 (subject identification) was completed this project year, and we have now turned attention exclusively to analyzing the data collected, the focus of a one year no-cost-extension that we were granted. Seventy subjects with collectively 112 fractures were identified/enrolled.

Major Task 4 (CT calculations) continues, with all CDs containing de-identified CT data having now been sent from Site 2 (SAMMC) to Site 1 (Iowa). We perform calculations of fracture severity and post-reduction contact stress as cases arrive in Iowa. The imaging data for 70 subjects with collectively 112 IAFs (see Table 1 for details) have been forwarded to Iowa for analysis. We have completed fracture severity analysis of 93 of the IAFs, with the remaining 19 either having significant metal artifact or antibiotic beads placed that preclude reliable segmentation (Figure 1) or including fractures not protocolled for study (cuboid, patella, etc.).

Table 1. Assortment of fractures and CT data collected for the study.		
Fracture location	Pre-op	Post-op
Calcaneus	42	8
Distal tibia	36	8
Proximal tibia	14	6
Talus	12	0
Distal femur	7	3
Acetabulum	1	0

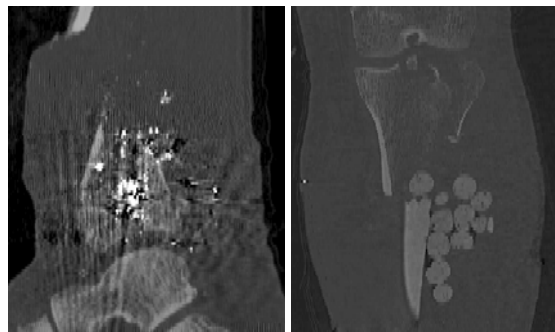


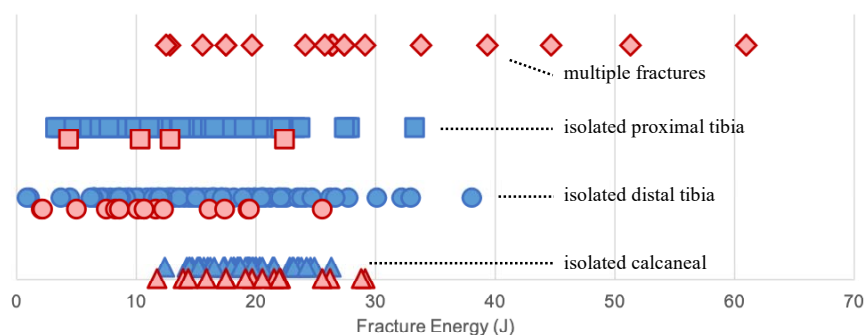
Figure 1. Two CT slices reflecting issues that preclude reliable segmentation, with the one to the left having substantial metal artifact from shrapnel and to the right having antibiotic beads placed.

Detailed report of progress on Major Task 4

In addition to the military cases, we have continued to analyze civilian IAF cases, with fracture energies having now been computed for 292 comparable IAFs (119 tibial pilon, 117 tibial plateau, and 56 calcaneal), as well as for 115 additional IAFs (22 distal radius and 93 acetabular) at joints for which we have limited comparable military cases. We were interested to see how the fracture energies vary between military and civilian cases (Table 2 & Figure 2), as well as between

Fracture type/location		N	Fracture Energy (J)	
			Mean	St Dev
multiple	military	18	28.4	13.3
proximal tibia	civilian	117	13.1	6.5
	military	4	12.4	7.5
distal tibia	civilian	119	15.3	7.4
	military	16	11.6	6.5
calcaneus	civilian	56	19.0	3.1
	military	16	20.3	5.2

Figure 2. Graphical comparison of the fracture energies computed in military subjects (red symbols) and civilian subjects (blue symbols), grouped by the location of isolated intra-articular fracture vs. the military multiple fractures.



isolated and multiple fracture scenarios in a single limb. Intuitively, cases involving multiple fractures in a single limb involve higher fracture energies, although other factors such as variation in loading rates (see below) may also be involved.

Fortuitously, in May 2017, we were introduced to a group at the University of Virginia's Center for Applied Biomechanics that has been doing cadaveric lower extremity fracture studies for the past 15 years. Dr. Robert Salzar leads the group doing this work and has been our primary point of contact. Their original studies focused on loading rates/conditions associated with common civilian fracture mechanisms, such as in automobile crashes. More recently, they have turned their attention to scenarios more akin to those experienced with blast injuries in the military. The motivation behind their work has been to define physical tolerance limits for the automotive industry and others in the context of protecting against extremity fracture. Data collected during their fracture experiments include accelerations, forces, displacements, bone strains, and video-radiography, with acoustic sensors used to precisely detect fracture initiation.

We immediately recognized this as an opportunity to complement our CT-based post hoc fracture severity analysis work with their direct studies of the actual fracture event. Pre-operative CT scans from 42 battlefield blast cases were analyzed for comparison with CT scans obtained from laboratory testing of 36 cadaveric lower extremity specimens. Three testing conditions designed to replicate battlefield blast fractures were used in the laboratory with low, intermediate, and high loading rates. Fracture energy measures were calculated from post-fracture CT scans using our validated methods. A new measure, the mean energy-release distance (MERD), was also calculated to characterize the location and distribution of fractures. The MERD was defined as the proximal distance from the distalmost aspect of the calcaneus at which 50% of the total fracture energy had been dissipated.

The battlefield blast cases had fracture energies of $15.2 \pm 8.1\text{J}$ (mean \pm SD) and MERDs of $63.4 \pm 42.4\text{mm}$ (Figure 3). The laboratory low, intermediate, and high impact conditions had fracture energies of $12.7 \pm 7.8\text{J}$, $19.5 \pm 8.8\text{J}$, and $23.5 \pm 7.7\text{J}$, along with MERDs of $33.6 \pm 31.2\text{mm}$, $53.6 \pm 31.7\text{mm}$, and $38.9 \pm 25.9\text{mm}$, respectively. There were no significant differences in the fracture energies between battlefield blast cases and the low ($p=0.33$) or intermediate ($p=0.13$) impact groups. The high impact group had significantly more energy released ($p=0.003$). Significant difference was seen between MERDs for the battlefield blast cases and the intermediate impact group ($p=0.019$), while no differences were seen with the intermediate ($p=0.48$) and high ($p=0.063$) impact groups.

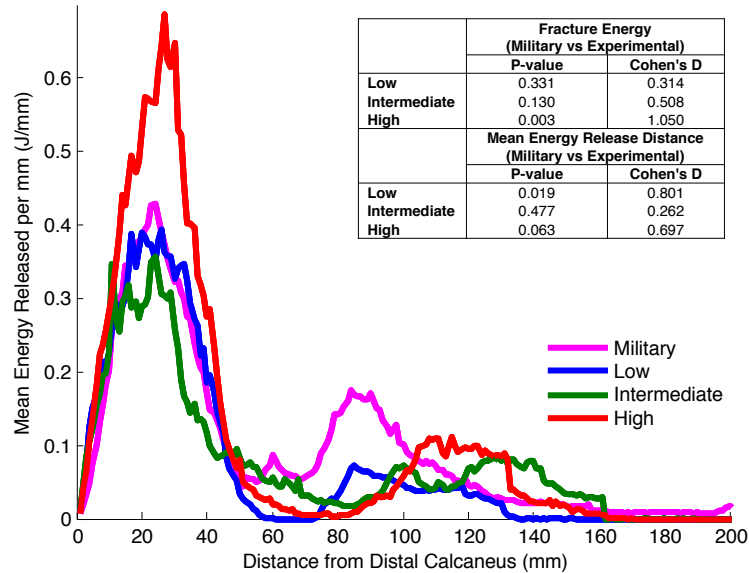


Figure 3. Plots of the mean fracture energy released across each group as it varies along the distance from the distalmost aspect of the calcaneus over the fractured segment of the lower extremity.

These results indicate that the intermediate laboratory impact protocol produced fractures most closely representative of battlefield blast injuries in both overall fracture energy and in its distribution (MERD). This methodology can be used to inform and improve injury models by bridging the gap between experimental and clinical results, and we hope to continue working with the group in Virginia to develop these ideas.

In the area of studying post-operative chronic contact stress elevation, we have needed to lean more heavily on our complementary civilian data. Most recently, we specifically chose to focus on contact stress elevation in acetabular IAFs and have adapted prior methods for this purpose. After obtaining Institutional Review Board (IRB) approval, a series of 75 patients at our institution who had undergone operative fixation of acetabular fractures between 2004 and 2016 were identified for having pre-operative and post-operative CT scans. Patients were excluded from study for having less than two-year radiographic follow-up, being under the age of 18 at the time of surgery, undergoing arthroplasty within the same hospital admission, or if they had associated femoral head fracture. Twenty-four patients declined to participate or were unreachable. Ten patients had undergone surgery within the past two years and thus did not have 2-year radiographic follow-up. One patient was 17 at the time of surgery. Of the remaining 40 patients, a total of 23 patients had adequate imaging and follow-up available for analysis.

Femoral and pelvic anatomy for each patient was segmented from post-operative CT scans to produce discrete element analysis (DEA) models using validated methods previously reported by our group (Townsend et. al. J Biomech. 2018 ;67:9-17). Bone geometries were extracted from CT using a semi-automated watershed-based algorithm. Errors in the automated surface detection and separation protocol were manually corrected, and triangulated surface models of

the anatomy were generated and smoothed. Articular surfaces were approximated by projecting the acetabular and femoral subchondral surfaces a uniform distance of 1mm then subsequently smoothing the projected surfaces toward sphericity using a custom iterative smoothing algorithm. The resulting approximations of the chondral geometries have been shown to yield accurate contact stress computations from fractured surfaces.

Radiographs obtained at two years after surgery or later were evaluated for arthritic changes by two independent evaluators. Each evaluator assigned a Tönnis grade to each hip using the modified Tönnis grading description scale. When there was disagreement between observers, an arbitrator reviewed the studies and determined Tönnis grade. Patients having Tönnis grades 0 and 1 were included in a no PTOA group and Tönnis grades 2 and 3 were included in a PTOA group. Those patients who went on to total hip arthroplasty or femoral head resection prior to two year follow up were considered as Tönnis grade 3 equivalents for radiographic purposes.

DEA models were then aligned to a coordinate system defined by Bergmann et al. (J. Biomech. 2001;34:859-71) based on patient-specific anatomic landmarks on the bone surface models. The walking gait data obtained in that study of instrumented total hips was discretized into 13 evenly spaced time increments. DEA was then used to compute contact stress over an entire gait cycle for each case using boundary conditions for forces and rotations based on patient-specific body weights and defined by the Bergmann et. al. study. Forces were applied to the femur and directed toward the hip as dictated by the Bergmann data. Cartilage was assigned isotropic linear-elastic material properties ($E=8\text{MPa}$, $\nu=0.42$).

A total of 23 patients (15 developed OA and 8 did not) and 10 healthy volunteers (serving as normal controls) were included in the final analysis. The average age of the patients was 40 ± 16.6 years at the time of surgery (42.5 ± 16.6 years in the OA group and 34.6 ± 15.1 years for the no OA group, $p=0.32$), and the average age of the controls was 34.6 ± 8.7 years ($p=0.34$). The average BMI was 29.9 ± 6.0 for the patients (29.5 ± 6.7 in the OA group and 30.8 ± 4.0 in the no OA group, $p=0.66$) and 35.0 ± 7.2 for the controls ($p=0.07$). There were 19 males and 4 females in the patient group (2 males and 17 females in the OA group) and 6 males and 4 females in the control group.

Qualitatively, the contact stress distributions in the control hips gradually varied over the surface. For the fractured hips, particularly those in the PTOA group, there were much more focal contact stress elevations that varied in location over the gait cycle (Figure 4), attributable to residual local articular surface incongruities. Our findings relating these contact stress measures to PTOA outcomes are detailed in the latter portion of the next section (see below).

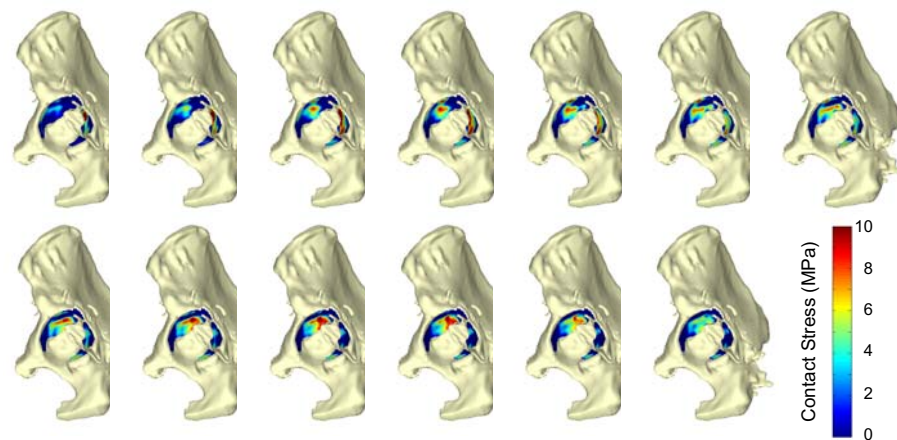


Figure 4. Contact stress distributions are computed at each of the 13 loaded poses for this fractured acetabulum to replicate the entire stance phase of gait.

Major Tasks 5 (PTOA radiographic frequency) and 6 (PTOA symptoms and quality of life) have presented challenges. Our partners at BAMC have screened hundreds of patient medical records and encountered challenges that were all expected, but not to the degree actually experienced. For one, the initial DoD trauma registry search had limitations based on coding. The BAMC team cast a broad net so not to miss potential cases, but in the process got a large number of ankle fractures and non-articular cases from inaccurate coding. Additional screening methods and fastidious review of cases has led to the successful accumulation of over 100 fractures now. However, the remaining difficulties include 1) a lack of follow-up radiographs or other records to comment on OA status and 2) a lack of requisite CT imaging. The follow up issue is a DoD medical system limitation that the team continues to struggle with, but we are hopeful that adequate medical follow-up will be obtained.

Detailed report of progress on Major Task 5

Clearly, the obtaining of reliable follow-up outcome data in the patients we have been analyzing has proven to be our most difficult challenge. To address this challenge, we chose to investigate our fracture energy results (Figure 5) by normalizing their values to characteristic joint-specific contact areas (Figure 6). This entailed pulling contact areas relevant to different

Comparison of Fracture Energy in Joints from Proximal to Distal

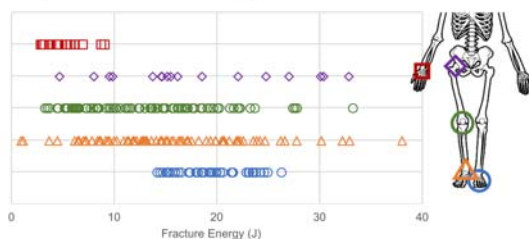


Figure 5. Graphical comparison of the fracture energies computed in civilian subjects with datapoints colored according to the joint (see skeleton to right for key).

Contact Area-Normalized Fracture Energy

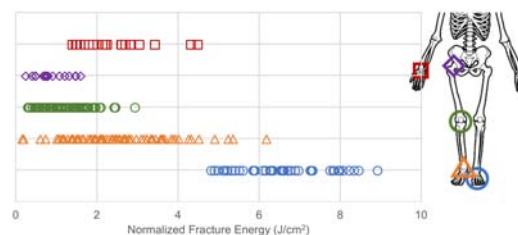


Figure 6. Graphical comparison of the fracture energies normalized to the characteristic contact area of the respective articular joint.

articular fractures (distal radius, acetabulum, tibial plateau, tibial pilon, and calcaneus) from the literature (Table 3). We additionally systematically searched the published literature for reported rates of PTOA after IAFs of these different joints, so that we could plot our fracture severity data against published rates of PTOA. Interestingly, once you normalize to account for the fact that energy transfer across the joint is distributed over the contact area of the articular surface, fracture energy much more accurately explains differences in PTOA propensity (Figure 7).

Table 3. Characteristic morphological properties of different articular joints.

	Cartilage Thickness (mm)	Contact Area (cm ²)
Calcaneus	1.02	2.95
Distal tibia	1.16	6.16
Proximal tibia	2.70	11.35
Acetabulum	1.88	20.74
Distal radius	0.60	2.01

In addition to variations in contact area, there are also variations in the thickness of the cartilage (Table 3) and in the density of the subchondral bone, both of which may also partly explain differences in PTOA rates in different joints. Thicker cartilage might, for instance, provide more material to deform and thereby further distribute the impact. If there are larger areas of contacting cartilage over which to disperse the energy, then the damage in any given region might be lessened. The literature reports differences in cartilage thickness across joints to be smaller than the differences seen in contact area. As there are other, larger anatomical

differences between these joints (e.g., presence/absence of a labrum, meniscus, etc.) it does pose a challenge for us to carefully consider other factors at play.

However, we would argue that variations in cartilage thickness are unlikely to be meaningful in this respect, because the fracturing impacts occur at such high rates of loading that there is very little opportunity for fluid flow in the cartilage, meaning that it is effectively much stiffer and therefore deforms little. For the ranges of cartilage thickness variation in these joints, it is hard to believe that the cartilage thickness appreciably influences the joint injury. As for variation in subchondral bone density across joints, it is implicitly captured by the fracture energy measurements, which incorporate bone density over inter-fragmentary surface areas involving subchondral bone.

Returning now to the PTOA risk attributable to IAF malreduction, we have investigated the implications of chronic contact stress elevation following surgical repair of the acetabular IAF cases (see above for detail of methods). The hips from healthy volunteers were exposed to an average maximum contact stress of 7.4 ± 2.0 MPa (mean \pm standard deviation). Hips from patients with acetabular fractures experienced an average maximum contact stress of 10.9 ± 3.4 MPa. Patients that developed PTOA had significantly higher maximum contact stresses in their hips than patients that did not (12.0 ± 3.8 MPa vs. 8.8 ± 0.7 MPa; $p=0.008$ – Figure 8). Patients that developed PTOA also had significantly higher maximum contact stresses than did subjects in the control group ($p<0.001$), while there was no significant difference in maximum contact stresses between the controls and the patients who did not develop PTOA ($p=0.068$). Over the course of the stance phase of gait, the PTOA group had higher maximum contact stress than the patients that didn't develop PTOA and the normal controls (Figure 9). The fracture patients that didn't develop PTOA also had consistently higher maximum contact stress than the normal control group.

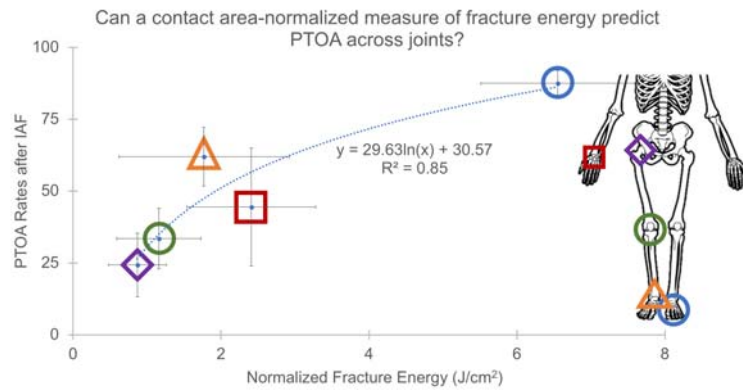


Figure 7. Correlation between the normalized fracture energies and the reported rates of PTOA for each of the joints of the body analyzed.

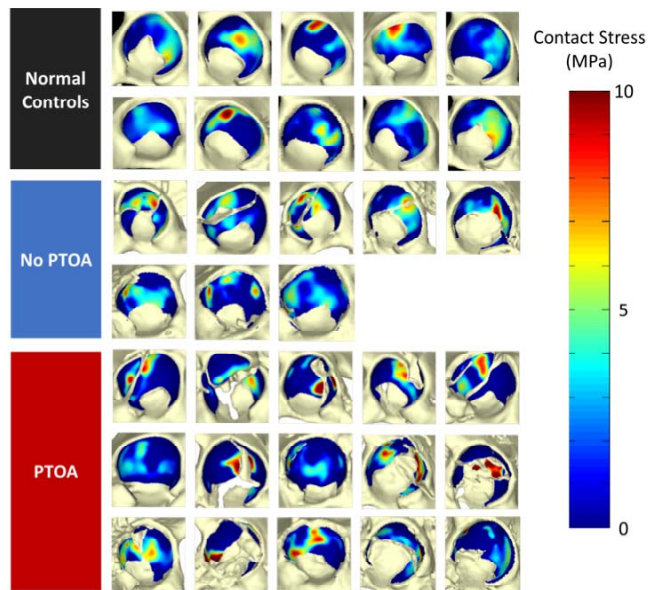


Figure 8. The contact stress distributions for the patients who had developed PTOA at two years after surgery were substantially more focal and had significantly higher peak values.

If we consider the peak maximum contact stress across the entire gait cycle, differences in the groups become more apparent (Figure 10). There appears to be a threshold of maximum contact stress around 11 MPa, above which patients predictably progress to PTOA. Of note, this level barely exceeds the highest maximum contact stress seen in the normal control group, indicating that even slight perturbations in the joint surface from normal in some cases may portend degeneration. However, in our data nearly half of the patients that developed PTOA (7/15) would be missed by this threshold, demonstrating the multifaceted nature of PTOA. These patients may have incurred irreparable damage from the initial fracture, have diminished regenerative capacity, or be predisposed to its development by a number of other factors that led to degeneration of their articular cartilage, despite a comparatively normal mechanical environment.

In an effort to improve the model of PTOA risk arising from chronic contact stress elevation, DEA was used to compute deleterious contact stress exposure above a damage threshold at each step in the gait cycle. The basic premise of this approach is that contact stress itself is not dangerous, and it is in fact required for normal cartilage functioning. However, above a certain level it is known to be deleterious to cartilage health. Therefore, to assess the effects of chronic mechanical insult, previous work by our group established the concept of a damage threshold above which contact stresses become deleterious to cartilage health. By ignoring contact stresses below the damage threshold and combining the duration and magnitude of suprathreshold contact stresses, we derived a means to estimate the dose of chronic mechanical insult. We refer to this dose as the contact stress over-exposure.

In our study, we selected the damage threshold to be 5 MPa, based on our prior work. These deleterious contact stresses were then computed at each of the 13 steps of the gait cycle and multiplied by the time spent in each of the steps to obtain a stress-time over-exposure metric. Summed over the gait cycle, the cumulative contact stress over-exposure experienced by the

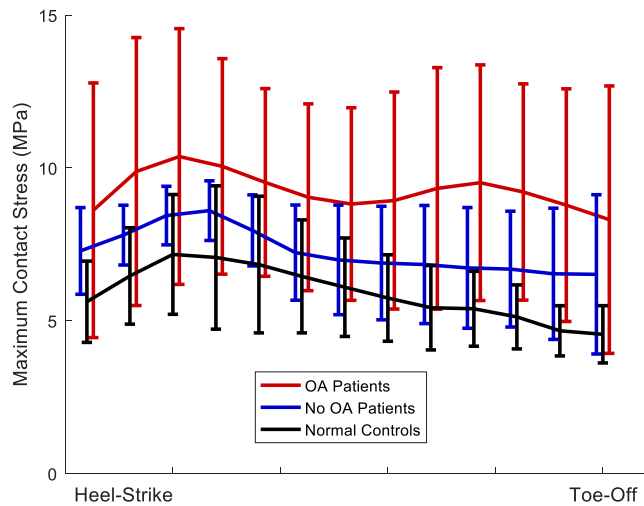


Figure 9. Over the entire stance phase of gait, the maximum contact stress in the OA group is higher than the no OA patients and normal hips.

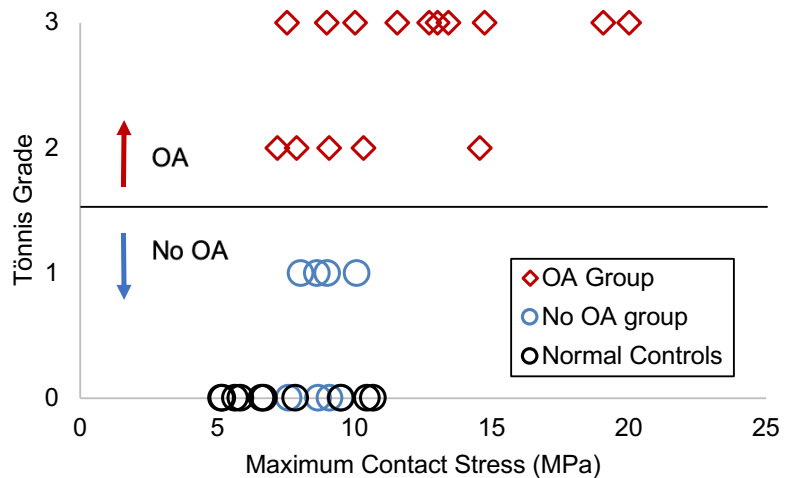


Figure 10. Elevated maximum contact stress is predictive of PTOA when contact stresses exceed those of normal.

articular surface was compared to Tönnis grades at 2 years post-operatively (Figure 11). For each patient, only the deleterious contact stress over-exposure was considered in our evaluation. We found a positive correlation (Pearson's correlation of 0.7) between the

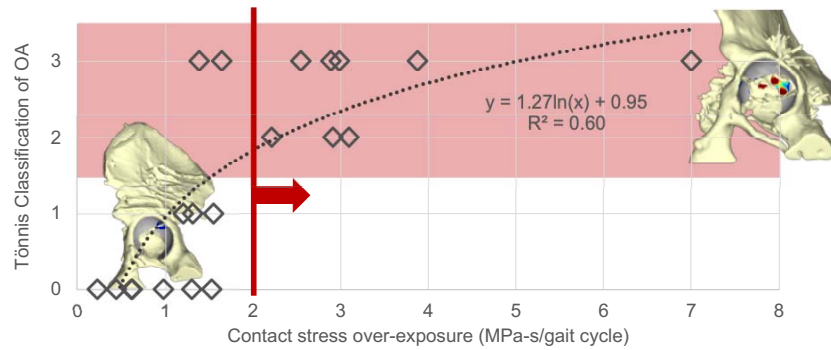


Figure 11. Maximum per gait cycle contact stress over-exposure vs. KL grade at minimum two-year clinical follow up.

maximum contact stress over-exposure and the Tönnis grade. The maximum contact stress over-exposure seen in the no PTOA group was 0.98 ± 0.45 MPa-s per gait cycle, while the PTOA group had maximum contact stress over-exposures of 3.06 ± 0.73 MPa-s per gait cycle, more than three times higher than in the no PTOA group. These differences were highly significant ($p < 0.0001$). Perhaps more significant clinically, these data present a clear exposure threshold above which cases predictably progress to PTOA. Using a 2 MPa-s/gait cycle threshold to predict which cases progressed to OA yields a sensitivity of 100% and a specificity of 83.3%.

To get an overview of how the exposures differed for the no PTOA and PTOA groups, they are divided top and bottom in Figure 12. Comparing the two groups, it becomes clear that acetabular fractures in the group that degenerated to PTOA had larger regions of higher contact stress over-exposures. In contrast, cases with minimal or no radiographic evidence of PTOA had less severe incongruities that resulted in regions of over-exposure that were smaller in size and magnitude.

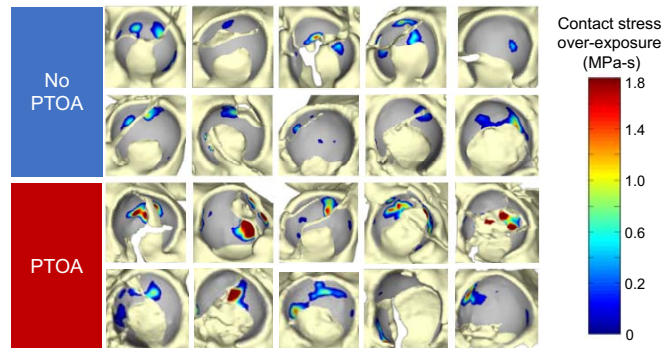


Figure 12. The distributions of contact stress over-exposure in the series of acetabular fractures studies are shown here, arranged according to their PTOA status.

What opportunities for training and professional development has the project provided?

Mr. Kevin Dibbern, the graduate research assistant on this project, is concurrently pursuing a PhD in Biomedical Engineering, and he is likely to complete his degree during the coming year. Dr. Anderson serves as his primary advisor, and in that capacity not only directs Mr. Dibbern's work, but also mentors him in related technical and professional development matters. This involves bi-weekly one-on-one meetings, having Mr. Dibbern give regular presentations in the laboratory related to this work, and having Mr. Dibbern attend national/international conferences at which his work is presented.

How were the results disseminated to communities of interest?

During the past year, one manuscript was accepted at the Journal of Orthopaedic Trauma and three additional manuscripts are written and in various stages of journal submission/review. Our

most recent findings have been presented in multiple venues. We presented at the 13th Annual Extremity War Injuries Symposium (sponsored by AAOS, SOMOS, OTA, and the ORS), the OARSI World Congress on Osteoarthritis, the 8th World Congress of Biomechanics, and at annual meetings of the ORS and of the American Society of Biomechanics. Most recently, we also submitted two abstracts for presentation at next year's ORS Annual Meeting.

What do you plan to do during the next reporting period to accomplish the goals?

In the coming quarter, work will continue further analyzing our data and collecting all of the patient outcomes that can be obtained. We will be continuing work on **Major Tasks 5 and 6**, which involves identifying, finding, and grading follow-up radiographs for PTOA status (KL grading). We will also be submitting manuscripts already prepared and writing additional ones.

4. Impact

What was the impact on the development of the principal discipline(s) of the project?

To our knowledge, we continue to be the only group utilizing objective quantitative fracture severity metrics to stratify PTOA risk after IAF. Correspondingly, we are the first to document a clear relationship between the acute mechanical insult to the joint and later PTOA risk. Additionally, our patient-specific computational modeling results are the first to demonstrate the relationship between cumulative contact stress over-exposure and PTOA in acetabular fractures. We are in the process of finalizing these analyses (and others) and have prepared manuscripts for submission (see Appendix).

What was the impact on other disciplines?

Nothing to Report

What was the impact on technology transfer?

Nothing to Report

What was the impact on society beyond science and technology?

Nothing to Report

5. Changes/Problems

Changes in approach and reasons for change

Nothing to Report

Actual or anticipated problems or delays and actions or plans to resolve them

Nothing to Report

Changes that had a significant impact on expenditures

Nothing to Report

Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents

Nothing to Report

Significant changes in use or care of human subjects

Nothing to Report

Significant changes in use or care of vertebrate animals.

Not Applicable

Significant changes in use of biohazards and/or select agents

Not Applicable

6. Products

Publications, conference papers, and presentations

▪ Journal publications

1. Rao K, Dibbern K, Day M, Glass N, Marsh JL, Anderson DD. Correlation of fracture energy with Sanders Classification and post-traumatic osteoarthritis following displaced intra-articular calcaneus fractures. *J Orthop Trauma*. (Accepted, Manuscript #: JOT9710R1). Federal support acknowledged.
2. Dibbern K, Kern A, Anderson DD. A universally applicable, objective CT-based method for quantifying articular fracture severity (submitted). Federal support acknowledged.
3. Dibbern K, McKinley TO, Marsh JL, Anderson DD. Toward a unifying understanding of the influence of acute fracture severity on risk of post-traumatic osteoarthritis following intra-articular fractures (ready for submission). Federal support acknowledged.
4. Thomas-Aitken H, Dibbern K, CarlLee T, Marsh JL, Willey M, Goetz J, Anderson DD. Elevated joint contact stress is associated with radiographic measures of osteoarthritis in operatively treated acetabular fractures at two years (ready for submission). Federal support acknowledged.

▪ Books or other non-periodical, one-time publications.

None during this reporting period.

▪ Other publications, conference papers, and presentations. [* indicates produced a manuscript]

1. Dibbern KN, Rivera JC, Marsh JL, Anderson DD. Objective metrics of tibial pilon fracture severity predict secondary amputation. 13th Annual Extremity War Injuries Symposium, January 21-23, 2018, Washington, DC.
2. Dibbern KN, Rivera JC, Marsh JL, Anderson DD. Objective assessment of tibial pilon articular fracture severity predictive of secondary amputation. 64th Annual Meeting of the Orthopaedic Research Society, March 10-13, 2018, New Orleans, LA.
3. Thomas HD, Dibbern KN, Holland TC, CarlLee T, Rao K, Marsh JL, Willey MC, Goetz JE, Anderson DD. Joint contact stress correlates with clinical measures of osteoarthritis in surgically reduced acetabular fractures. 64th Annual Meeting of the Orthopaedic Research Society, March 10–13, 2018, New Orleans, Louisiana. (*)
4. Anderson DD. Alex Stacoff Lecture: Enabling Post-Traumatic OA Risk Prediction from Pathomechanics. 2018 International Foot and Ankle Biomechanics (i-FAB) Meeting, April 10, 2018, New York City, New York.

5. Thomas HD, Dibbern KN, Holland TC, Marsh JL, Willey MC, Goetz JE, Anderson DD. Elevated contact stress after acetabular fracture correlates with development of radiographic OA. 2018 OARSI World Congress on Osteoarthritis, April 26–29, 2018, Liverpool, United Kingdom. (*)
6. Anderson DD. Enabling Post-Traumatic Osteoarthritis Risk Prediction from Pathomechanics. Engineering Solutions for Health: Biomedical Engineering Research Strategy, June 6, 2018, University of Calgary, Calgary, AB Canada.
7. Dibbern KN, Perry BJ, Spratley EM, Salzar RS, Rivera JC, Anderson DD. Novel severity measures link fractures from cadaveric experiments to those in battlefield blast cases. 8th World Congress of Biomechanics, July 8–12, 2018, Dublin, Ireland.
8. Thomas-Aitken HD, Dibbern KN, Holland TC, Marsh JL, Willey MC, Goetz JE, Anderson DD. Elevated contact stress after acetabular fracture correlates with the development of radiographic OA. 8th World Congress of Biomechanics, July 8–12, 2018, Dublin, Ireland. (*)
9. Dibbern KN, Holland TC, Thomas-Aitken HD, CarlLee T, Willey MC, Goetz JE, Marsh JL, Anderson DD. Contact stress over-exposure correlates with OA development in acetabular fractures. 42nd Annual Meeting of the American Society of Biomechanics, August 8–11, 2018, Rochester, Minnesota. 2018. **[Received ASB Clinical Biomechanics Award.]**

Website(s) or other Internet site(s)

Nothing to Report

Technologies or techniques

Our prior objective, CT-based methods for determining the energy expended in a bone fracture were extended to enable their use in more fracture types. The new methodology requires only a pre-operative CT-scan of the fractured joint. The CT images are then segmented, identifying all bone fragments to generate 3D models of the fracture fragments. Surfaces are then smoothed to remove imaging artifacts and to prepare the data for use in a surface classification algorithm. An automated classifier then identifies fractured surfaces on the fragments, with a graph cut method used to create a clear boundary between the intact and fractured bone surfaces. Manual adjustment of this boundary is performed to finalize the fractured surface identification. The CT Hounsfield Unit intensities are then sampled along the fractured surface for use in obtaining a bone density distribution over the surface. The fractured areas are then scaled by these location specific densities and multiplied by a density dependent energy release rate to obtain the fracture energy. Articular comminution can be quantified by measuring the fracture edge length along the articular surface from the fractured surface boundaries. The new methodology was validated by comparing the fracture energies obtained for a series of 20 pilon fractures that had previously been assessed using the existing methods.

We recognize the need for broad dissemination of the research methods developed in the course of this work that allow study of the pathways responsible for PTOA. Perhaps the most effective means for sharing the techniques is through the presentation of our findings at scientific meetings and as peer-reviewed published manuscripts. In the latter case, we will submit or have submitted on our behalf to the National Library of Medicine's PubMed Central an electronic version of any final, peer-reviewed manuscripts upon acceptance for publication, to be made

publicly available no later than 12 months after the official date of publication. We will strive to produce such scientific outputs in a timely manner and to report on all relevant data derived during the project in as broad a range of venues as possible.

Inventions, patent applications, and/or licenses

Nothing to Report

Other Products

Nothing to Report

7. Participants & Other Collaborating Organizations

What individuals have worked on the project?

Name: Donald D. Anderson, PhD

Project Role: PI

Researcher Identifier (e.g. ORCID ID): 0000-0002-1640-6107

Nearest person month worked: 2.4

Contribution to Project: Dr. Anderson leads the research team at the University of Iowa, guiding development and analysis related to the project.

Name: J. Lawrence Marsh, MD

Project Role: Investigator

Researcher Identifier (e.g. ORCID ID): 0000-0002-3494-6289

Nearest person month worked: 0.6

Contribution to Project: Dr. Marsh is the clinical lead at the University of Iowa, providing insight regarding the scope of the clinical problem and ensuring clinical applicability of decisions related to the project.

Name: M. James Rudert, PhD (30 Sep 2017 – 30 Mar 2018)

Project Role: Investigator

Nearest person month worked: 4

Contribution to Project: Dr. Rudert, an expert in mechanical measurement and fracture testing/simulation work, works closely with Mr. Dibbern to support measurements and computation. Dr. Rudert was taken off the team as of 30 Mar 2018 as he retired.

Name: Joshua E. Johnson, PhD (01 Jul 2018 – 29 Sep 2018)

Project Role: Investigator

Nearest person month worked: 4

Contribution to Project: Dr. Johnson was hired to replace Dr. Rudert on the team, and he began employment 01 Jul 2018.

Name: Kevin Dibbern, MS

Project Role: Graduate Research Assistant

Researcher Identifier (e.g. ORCID ID): 0000-0002-8061-4453

Nearest person month worked: 6

Contribution to Project: Mr. Dibbern is actively involved developing algorithms, writing analysis code, and performing analysis of the CT data.

Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?

Nothing to Report

What other organizations were involved as partners?

Nothing to Report

8. Special Reporting Requirements

COLLABORATIVE AWARDS: The Collaborating/Partnering PI at SAMMC (Dr. Jessica Rivera) is submitting a separate progress report for that site.

9. Appendices

A collection of journal publications and abstracts (please see above *Products* for a complete listing) from the past year that supplements, clarifies and supports the text of this report are attached as appendices.

Journal of Orthopaedic Trauma
Correlation of Fracture Energy with Sanders Classification and Post-Traumatic Osteoarthritis following Displaced Intra-Articular Calcaneus Fractures
 --Manuscript Draft--

Manuscript Number:	JOT9710R1
Full Title:	Correlation of Fracture Energy with Sanders Classification and Post-Traumatic Osteoarthritis following Displaced Intra-Articular Calcaneus Fractures
Article Type:	Original Article
Keywords:	Fracture energy; Calcaneus Fractures; Intra-articular Fractures; Fracture Severity; Post-Traumatic Osteoarthritis
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	Natalie Glass, PhD
	J. Lawrence Marsh, MD
	Donald Anderson, PhD
Order of Authors Secondary Information:	

1 **Correlation of Fracture Energy with Sanders Classification and Post-Traumatic Osteoarthritis**
2 **following Displaced Intra-Articular Calcaneus Fractures**

3 **Karan Rao, BSE, Kevin Dibbern, MS, Molly Day, MD, Natalie Glass, PhD, J. Lawrence Marsh,**
4 **MD, Donald D. Anderson, PhD**

5 Department of Orthopaedics and Rehabilitation, the University of Iowa, Iowa City, Iowa.

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17 are those of the author and are not necessarily endorsed by the Department of Defense. The authors
18 would like to acknowledge Dr. Phinit Phisitkul for his expert assessment of KL grades and Sanders
19 classification. We also acknowledge the dedicated segmentation efforts of Mr. Denis Cuvalo.

1 **ABSTRACT**

2 **Objectives:** To quantify fracture severity for a series of displaced intra-articular calcaneal fractures
3 (DIACFs) and correlate it with Sanders classification, post-traumatic osteoarthritis (PTOA), and patient
4 outcomes.

5 **Methods:** 36 patients with 48 DIACFs were selected for retrospective review. Pre-op CT scans were
6 used to grade fractures according to the Sanders classification and to quantify fracture severity. Fracture
7 severity was objectively quantified using a CT-based measure of fracture energy. PTOA was assessed
8 on follow up radiographs using the Kellgren-Lawrence scale. Patient outcomes were assessed using the
9 Short Form 36 (SF-36) questionnaire and a visual analogue scale (VAS) pain score.

10 **Results:** Fracture energies for the 48 DIACFs ranged from 14.1 to 26.2 J (19.3 ± 3.1 J) and correlated
11 with Sanders classification ($\rho=0.53$, $p=0.0001$); type I [16.3 ± 0.9 J]; type II [18.0 ± 2.7 J]; type III
12 [20.8 ± 2.8 J]; type IV [22.0 ± 0.7 J]. Fracture energy was higher for fractures in which the subtalar joint
13 developed PTOA (19.5 ± 2.7 J) than for those that did not (18.9 ± 3.3 J), but the difference did not reach
14 statistical significance. Sanders classification predicted PTOA risk (OR=4.04, 95% CI=1.43-11.39,
15 $p=0.0084$). No relationship was observed between fracture energy and VAS pain scores. A higher
16 fracture energy correlated to lower SF-36 scores.

17 **Conclusions:** Fracture energy positively correlates to the Sanders classification for DIACFs, which can
18 be used to identify more severe fractures at greater risk for progressing to PTOA.

19 **Level of Evidence:** Prognostic, level III

20 INTRODUCTION

21 The energy involved in fracturing a bone, by definition the fracture energy, can be measured
22 from clinical CT scan data and used to objectively quantify fracture severity. CT-based methods for
23 quantifying fracture energy have previously been described for tibial plateau and pilon fractures.¹⁻³
24 Fracture energy as a measure of severity may improve upon current fracture classification systems,
25 which are categorical and prone to poor inter-observer reliability.⁴

26 Displaced intra-articular calcaneal fractures (DIACFs) frequently result in post-traumatic
27 osteoarthritis (PTOA). Previous studies have shown that fracture energy correlates with PTOA risk in
28 tibial pilon fractures.^{1, 2, 5} However, the prognostic value of fracture energy in predicting PTOA risk and
29 clinical outcomes has not been evaluated in DIACFs. Our objective CT-based measurement technique
30 has the potential to impact clinical research, treatment decisions, and counseling of patients with
31 DIACFs regarding progression of osteoarthritis.

32 The primary purpose of the present study was to quantify fracture severity by calculating fracture
33 energy for a series of DIACFs and to correlate these values with fracture classification and PTOA risk.
34 A secondary purpose was to correlate fracture severity with patient-reported clinical outcomes. We
35 hypothesized that fracture severity would correlate with Sanders classification and be a significant
36 predictor of PTOA following DIACFs. We also hypothesized that patients sustaining fractures with
37 greater fracture energy would have poorer clinical outcomes.

38 METHODS

39 To assess fracture energy and correlate it with key dependent variables, a convenience sample of
40 patients with DIACFs was chosen from a larger series of patients that were identified. Thirty-six patients
41 with 48 DIACFs were selected for study from among 153 patients that had been treated (Figure 1). The
42 patients selected were age ≥ 18 years, had available electronic pre-op and post-op CT scans, and good

43 quality post-op and follow up radiographs. Patients age < 18, extra-articular fractures, and patients
44 without pre-op CT scans were excluded. The patients' charts and radiographs were accessed
45 retrospectively after approval of the IRB. Demographic data and patient characteristics are shown in
46 Table 1.

47 *Pre-op fracture classification*

48 Pre-op CT scans were used to determine the Sanders classification.⁶ A fellowship trained
49 orthopedic trauma surgeon, a fellowship trained orthopedic foot and ankle surgeon, and a PGY-3
50 orthopedic resident independently classified each fracture using Sanders classification. Discrepancies
51 were adjudicated by majority vote of 3 members, where each member had one vote. 11/48 fractures had
52 a one-grade discrepancy in independent evaluation of Sanders classification, and an additional 2/48 had
53 a separation of two grades, prior to subsequent consensus.

54 *Operative protocol and articular step off*

55 Fractures were treated with percutaneous reduction, using multiple small stab incisions and
56 fluoroscopy to guide manipulation of articular fragments using cork screws or Steinmann pins, with
57 subsequent fixation using 3.5 and 4.0 mm screws.^{7,8} All procedures were performed by either a
58 fellowship-trained orthopedic trauma surgeon or a fellowship-trained orthopedic foot and ankle surgeon.
59 Surgical reduction was assessed by measuring the residual step-off at the articular surface using a semi-
60 automated 3D step-off measurement tool coded in MATLAB (MathWorks, Inc., Natick, MA) software.
61 Three patients with 4 fractures did not have post-op CT scans available to assess articular step off but
62 were still included in the study.

63 *Assessment of fracture severity*

64 The CT-based approach for assessing fracture severity relies on computing fracture energy,
65 which is quantified by measuring the fracture-liberated surface area and accounting for bone density.^{1,5}

66 Mechanical energy involved in a fracture liberates new surface area in a brittle solid (bone), and that
67 energy is proportional to the inter-fragmentary surface area.^{1, 2, 5, 11} Previous studies have shown this
68 method to accurately calculate fracture energy.² To determine fracture-liberated surface area, custom-
69 written MATLAB software was used to identify fracture fragments from CT images. CT intensities and
70 local fracture lines were used to further classify surfaces of bone fragments as cortical, subchondral, or
71 inter-fragmentary. An image segmentation expert manually confirmed the accuracy of the surface
72 classifications and made modifications as needed. The inter-fragmentary surface area was computed for
73 each fractured face identified on the model. The Hounsfield Unit intensities from the CT scan were
74 sampled at each vertex of these fractured faces, averaged, and scaled by a conversion factor to obtain the
75 location-specific bone density for each face. This location-specific bone density was then used to
76 appropriately scale the fracture-liberated surface area by density-dependent energy release rates to
77 obtain the fracture energy for each fractured area (Figure 2). This entire process takes on the order of
78 four hours from the time the CT study is received until the fracture energy is obtained.

79 *Assessment of PTOA and clinical outcomes*

80 PTOA was assessed on follow up radiographs using the Kellgren-Lawrence (KL) scale.⁹ The
81 same three clinicians independently assigned a KL grade to the subtalar joint using available post-op
82 AP, lateral, and Broden radiographs of the calcaneus. The radiographs were assessed at follow up times
83 ranging from 19 to 84 months, with a median follow up time of 43 months. Disagreement in evaluation
84 of KL grades was adjudicated by majority vote of all three evaluators. A KL grade ≥ 2 met criteria for
85 PTOA.

86 Patients were clinically evaluated using functional outcome questionnaires scored from chart
87 review. To evaluate clinical health score trends, fracture energy values were divided into three
88 categorical energy ranges (“low,” “medium,” and “high”) with the goal of having an approximately
89 equal number of fractures in each category. Two clinical health outcome scores were obtained: the

90 visual analog scale (VAS) for pain, and the Short Form 36 (SF-36) quality of life survey. The SF-36 is a
91 widely used quality of life survey composed of a physical component summary (PCS) and a mental
92 component summary (MCS), with each category scoring from 0-100, and higher scores representing
93 better outcomes.¹⁰

94 *Statistical methods*

95 Statistical analyses were completed using SAS software version 9.4 (SAS Institute, Inc., Cary,
96 NC). A P-value <0.05 was considered statistically significant. For continuous outcomes between two
97 groups, the t-test was applied for variables that were normally distributed, and the Wilcoxon Rank Sum
98 test was used for variables without normal distributions. Adjustments for multiple comparisons were
99 completed. Spearman correlation coefficients were used to describe relationships between fracture
100 energy, Sanders classification, VAS pain, SF-36 score, and step off. Logistic regression was used to
101 model the association between fracture energy, Sanders classification, and PTOA risk. Inter-observer
102 reliability was assessed using Kendall's τ coefficient of concordance.

103 **RESULTS**

104 *Fracture energy and Sanders classification as predictors of PTOA*

105 Of the 48 calcaneus fractures, 2 (4%) were classified as Sanders type I, 24 (50%) as type II, 19
106 (40%) as type III, and 3 (6%) as type IV (inter-rater reliability coefficient of concordance $\tau = 0.3$). The
107 fracture energies for the 48 DIACFs ranged from 14.1 to 26.2 J, with a mean \pm standard deviation of
108 19.3 ± 3.1 J. There was a statistically significant, positive linear correlation between Sanders
109 classification and mean fracture energy ($\rho=0.53$, $p = 0.0001$). The mean \pm SD fracture energies for
110 each Sanders class are as follows: type I [16.31 ± 0.98 J] ($n=2$), type II [18.03 ± 2.73 J] ($n=24$), type III
111 [20.79 ± 2.80 J] ($n=19$), and type IV [21.98 ± 0.73 J($n=3$)] (Figure 3).

112 Mean fracture energy and follow up time, along with the number of fractures for each
113 radiographic grade of PTOA, are shown in Table 2. Prior to consensus sessions, 14/48 fractures had a
114 one-grade discrepancy in independent evaluation of KL grades, an additional 4/48 fractures had a two-
115 grade discrepancy, and 1/48 fractures had a three-grade discrepancy, as assessed by a PGY-3 resident
116 and an orthopedic trauma surgeon (inter-rater reliability coefficient of concordance $\tau = 0.6$, $p=0.0074$).
117 Fracture energies showed overlap across different grades of PTOA. Stratifying these data by the
118 presence of radiographic PTOA ($KL \geq 2$), the fracture energy was higher for fractures in which the
119 subtalar joint developed PTOA (19.5 ± 2.7 J) than for those fractures in which the subtalar joint did not
120 (18.9 ± 3.3 J), but the difference did not reach statistical significance (OR = 1.37, 95% CI = 0.53-3.51,
121 $p=0.52$) (Figure 4).

122 Twenty-nine out of 48 subtalar joints (60%) showed radiographic evidence of PTOA. The
123 median follow-up time for joints that developed PTOA was 49.0 (20.9-84.0) months. The average
124 follow-up time for joints that didn't develop PTOA was 28.0 (19.4-58.0) months. Follow up time was
125 associated with PTOA (OR=3.208, 95% CI=1.389–7.405, $p=0.0063$).

126 Eight patients (22%) with 10 affected subtalar joints were treated with subtalar arthrodesis (KL =
127 4). The median time to subtalar fusion, from the time of injury, was 34.6 (15.0-78.0) months. The
128 fracture energies observed for these fractures (19.4 ± 3.5 J) were not significantly different from those
129 that did not result in fusion (19.3 ± 3.0 J, OR= 1.05, 95% CI = 0.34-3.24, $p=0.9343$).

130 Sanders classification positively correlated with the risk of developing PTOA (OR = 4.04, 95%
131 CI = 1.43-11.39, $p=0.0084$), and the results were significant even when adjusted for follow-up time
132 between the PTOA and non-PTOA groups (OR=4.60, 95%CI = 1.30-16.28, $p=0.0179$). For Sanders type
133 I fractures, no evidence of PTOA was observed. For type II fractures, an equal number of subtalar joints
134 developed PTOA as did not. A greater percentage (72%) of subtalar joints developed PTOA in Sanders

135 type III and IV fractures (Table 3). Sanders classification did not correlate with the likelihood of subtalar
136 arthrodesis (OR=1.39, 95% CI = 0.48-4.00, p=0.5399).

137 *Clinical outcomes and functional scores*

138 VAS pain scores were available for all 36 patients, and SF-36 scores were available for 28 of 36
139 patients. VAS pain scores were lowest for intermediate energy fractures, and similar for low energy and
140 high energy fractures (Table 4). Taken across the aggregate fracture energy range, there was a weak
141 negative correlation between fracture energy and VAS pain scores ($\rho = -0.13$, $p = 0.3764$). Patient-
142 reported SF-36 PCS were lower for high energy fractures. This result was more pronounced in patients
143 with bilateral fractures ($\rho = -0.76$, $p = 0.0018$, $n = 14$). There were no significant associations observed
144 between fracture energy and SF-36 MCS, although there was a trend for lower scores with higher energy
145 fractures.

146 Somewhat unexpectedly, patients who developed PTOA did not report significantly higher VAS
147 pain scores than patients who did not (Table 5). However, both SF-36 PCS and MCS were lower among
148 patients who developed PTOA than in those who did not [PCS (PTOA: 34.7, no PTOA: 45.0; $p = 0.013$),
149 MCS (PTOA: 47.9, non PTOA: 55.8; $p = 0.045$)]. An inverse relationship was observed between Sanders
150 classification and VAS pain scores. Although generally decreasing with higher Sanders classification,
151 SF-36 MCS scores did not differ significantly across Sanders fracture types, while SF-36 PCS scores
152 significantly decreased.

153 *Outcomes by surgical reduction*

154 With respect to the quality of surgical reduction, 25 of 44 fractures (56.8%) measured a step of <
155 2 mm, and 19 of 44 fractures (43.2%) measured a step-off > 2 mm. No correlation was observed
156 between fracture energy and articular step-off. A non-significant positive association was observed

157 between articular step-off and KL grades (Table 6). Similarly, a positive correlation was observed
158 between Sanders classification and articular step off, but the finding was also not statistically significant.

159 **DISCUSSION**

160 *Correlation of fracture energy with Sanders classification*

161 The energy range for DIACFs was found to be 14.14–26.87 J. Dibbern, et al used a similar
162 methodology and reported fracture energies for tibial plateau fractures (3.2-33.2 J) and for pilon
163 fractures (3.6-32.2 J).³ Thomas et al reported pilon fracture energy range from 5.2-27.2 J.¹ Compared to
164 plateau and pilon fractures, the energy range for calcaneus fractures appears to be narrower and focused
165 on the upper end of the spectrum, suggesting it may take consistently more energy to break the
166 calcaneus. Although the shape and density of the calcaneus cancellous bone is different than the plateau
167 and pilon, the MATLAB software accounts for differences in Hounsfield CT density values, which
168 reflect the differences in density of the cancellous bone. Fracture morphology and the size of the
169 articular contact area for a given joint both influence the energy absorption.^{13, 14} The shorter length of
170 the calcaneus and the smaller contact area may limit the amount of energy absorbed, suggesting the
171 calcaneus shatters in response to a higher, more concentrated distribution of energy compared to long
172 bones such as the tibia.

173 Fracture classification systems are often used to provide a clinician-assessed indicator of fracture
174 severity but suffer from poor inter-observer reliability when clinicians place fracture patterns into
175 categorical classification schemes.^{3,4} This study demonstrated poor inter-observer reliability in
176 classifying DIACFs by the Sanders Classification (concordance $\tau = 0.6$, $p=0.0074$). The Sanders
177 classification is commonly used to assess DIACFs and has been previously found to be prognostic of
178 long-term patient outcomes.¹⁵⁻¹⁸ We found that fracture energy generally increased with Sanders
179 classification. This is an expected result; Sanders classification is based on the number of fracture lines

180 through the posterior facet. More fracture lines through the posterior facet generally correlates with
181 greater inter-fragmentary surface area, translating into higher energy. There was, however, considerable
182 overlap among classification of fracture types and fracture energy, which may in part be explained by
183 the fact the Sanders classification assesses only the number of intraarticular fracture lines, whereas the
184 fracture energy calculation accounts for extra-articular extension of the fracture which may vary across
185 otherwise similar Sanders grades.

186 *Fracture energy as a predictor of PTOA*

187 In this study, 61% of patients developed radiographic evidence of PTOA, and 22% of patients
188 progressed to subtalar joint fusion, at a median of 36 months post injury. Previous studies have
189 demonstrated that fracture severity metrics applied to tibial pilon fractures strongly correlate with PTOA
190 risk.^{1, 2, 4} In this study, this relationship was less evident for DIACFs. While mean energy was higher for
191 fractures in which the subtalar joint progressed to PTOA, there was significant energy overlap with
192 those that did not. The pathogenesis of PTOA is heterogeneous and may result from persistence of a
193 pathologic process initiated at the time of initial joint trauma or a combination of pathological and
194 inflammatory processes that take place in damaged tissue.¹⁹ Additionally, independent risk factors such
195 as obesity, smoking, age, sex, and activity levels are likely to confound the relationship between fracture
196 energy and PTOA.

197 This study also assessed the effect of another important variable, the residual mechanical
198 environment caused by persistent articular step offs. Multiple studies have suggested that fractures with
199 an incongruous reduction (i.e., step off > 2 mm) are associated with early PTOA; however, evidence is
200 less clear on the relationship between poor reduction and worse long-term clinical outcomes.^{11, 19-22} In
201 this study, fracture energy did not correlate with articular step off, but there was a positive association
202 between KL grade and articular step off, as well as between Sanders classification and articular step off;
203 however, these differences were not significant. Articular step off is an important source of expected

204 PTOA, but other factors including cartilage loss at time of surgery, and abnormal alignment of the body
205 leading to uneven wear also influence PTOA risk from the time of surgical intervention to arthritis
206 development.

207 *Correlation to clinical outcomes*

208 The clinical outcome assessed by SF-36 scores significantly correlated with PTOA. Fracture
209 energy showed a weak negative correlation to SF-36 PCS scores, and scores were significantly different
210 between PTOA and non-PTOA groups after an energy cutoff of 20 J (p=0.049). SF-36 scores also
211 decreased with increasing levels of Sanders classification. These findings are consistent with previous
212 literature reporting SF-36 outcome scores after DIACFs.

213 Trends with the VAS pain scores were less definitive. VAS pain scores did not correlate with
214 either fracture energy or Sanders classification in any predictable or expected way. In addition, they did
215 not correlate with PTOA at follow up. Interestingly, VAS pain scores were highest for “low” energy
216 fractures and lowest for “intermediate” energy fractures. VAS scores were higher for patients who
217 showed radiographic evidence of PTOA. VAS pain scores did not relate to the Sanders classification.
218 Sanders classification has been shown to be prognostic with SF-36 and VAS pain scores, but sample
219 size was a limitation in the present study for observing similar statistically significant trends.

220 *Limitations*

221 KL grading has previously been demonstrated in the literature to be subjective with moderate
222 inter-observer reliability in the subtalar joint.²³⁻²⁶ In this study, inter-observer reliability in assessing
223 PTOA on plain radiographs was in the moderate range ($\tau=0.6$). The lack of CT imaging to assess PTOA
224 was a limitation, and further research assessing PTOA with weight bearing CT scans may more
225 accurately characterize subtalar PTOA. Another limitation was the form in which the VAS pain scores
226 were charted on a 3 point range in patient records (for example, “moderate pain, VAS 4-6”), instead of a

227 true 10 point scale. This may explain the significant overlap in pain scores and limited statistical
228 significance observed with fracture energy.

229 Sample size was also a limitation. Ideally, a higher fracture energy suggests a more severe
230 fracture pattern (which we observed with the Sanders classification), which in turn should reflect a
231 higher PTOA risk. Possible confounding factors between fracture energy and PTOA risk include quality
232 of reduction, gender, age, BMI, and comorbidities. Radiographic PTOA was assessed in this study.
233 Defining PTOA from a biological and pain perspective creates additional complexities as the
234 pathogenesis of PTOA is in itself complex, as is how patients interpret and report pain. Sanders
235 classification positively correlated with the risk of developing PTOA, consistent with literature,¹⁸ but
236 did not correlate with risk of subtalar fusion. Weak positive correlations between KL grades and
237 articular step off, as well as between Sanders classification and articular step off were observed, which
238 may have reached statistical significance with a larger sample size.

239 **CONCLUSIONS**

240 CT-based measurement of fracture energy in DIACFs showed a narrower range compared to
241 tibial pilon and plateau fractures and is at the upper end of energy, suggesting that it takes consistently
242 more energy to break the calcaneus. Fracture energy correlated with Sanders classification, but several
243 factors contribute to significant energy overlap between Sanders categories. Fracture energy, Sanders
244 classification and articular step off all correlate with subsequent PTOA, but the association of fracture
245 energy with PTOA is not as strong as it was in the tibial pilon.

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306 **Figure Legends**

307 **Figure 1.** Selection criteria for study.

308 **Figure 2. Superior views of a Sanders type III intra-articular fracture of the calcaneus.** From left to
309 right: (a) patient-specific CT slice with overlay of image segmentation of fracture fragments; (b) two
310 fracture lines coursing through the posterior talar articular surface demonstrating a Sanders type III
311 fracture pattern; (c) 3D model of the fracture generated by custom-written MATLAB software; (d)
312 exploded view showing inter-fragmentary bone surfaces and CT-derived densities used to calculate the
313 fracture energy. [A= anterior talar articular facet; M = middle talar articular facet; P = posterior talar
314 articular facet.

315 **Figure 3.** Relationship between the Sanders classification and fracture energy. Diamond markers
316 represent the mean and the horizontal bars represent the standard deviation. ($\rho=0.53$, $p = 0.0001$).

317 **Figure 4. Fracture energy (J) vs PTOA development in the subtalar joint for calcaneus fractures.**
318 29 subtalar joints developed radiographic PTOA with an energy of $19.5 \text{ J} \pm 3.3 \text{ J}$. 19 subtalar joints did
319 not show radiographic evidence of PTOA, with a mean energy of $18.9 \text{ J} \pm 2.8 \text{ J}$. $P=0.5314$.

Table 1

Table 1. Patient characteristics

Total patients/calcanei	36/48
Sex (patients/calcanei):	
Male	33 (91.7%)/44 (91.7%)
Female	3 (8.3%)/4 (8.3%)
Age (n =36)	18-70 years (43.1±11.8)
BMI (n=35)	26.9±4.0 kg/m ² (19.5-36.8)
Mechanism of injury:	
Fall	34 (94%)
Car accident	2 (6%)
Unilateral fracture	24 (67%)
Bilateral fractures	12 (33%)
Follow up time (months)	19.4-84 (43.6±18.4)
Sanders classification:	
I	2 (4%)
II	24 (50%)
III	19 (40%)
IV	3 (6%)
Open injury	3/36 (8%)
Poly-trauma	12/36 (33%)
Tobacco users	15/36 (42%)
Workers compensation	15/36 (42%)
Underlying disease	13/36 (36%)

BMI: body mass index; KL: Kellgren-Lawrence

Table 2: Number of fractures, mean energy (J) (standard deviation), and median follow up time (min-max) for each radiographic stage of osteoarthritis.

<i>KL Grade</i>	<i>Number of fractures</i>	<i>Fracture energy (J) mean (SD)</i>	<i>Follow up time (months) median (min-max)</i>
0	9 (18.8%)	18.2 (1.5)	32.1 (19.4-55.0)
1	10 (20.8%)	19.6 (3.5)	26.1 (19.4-58.0)
2	9 (18.8%)	19.5 (3.5)	47.0 (23.0-68.0)
3	8 (16.7%)	19.7 (2.4)	48.5 (20.9-84.0)
4	12 (25%)	19.4 (3.9)	56.5 (24.2-84.0)

KL: Kellgren-Lawrence; SD: standard deviation

Table 3

Table 3: Number and percent of fractures in which the subtalar joint progressed to PTOA and joint fusion, across Sanders classification.

<i>Sanders type</i>	<i>PTOA absent (KL <2)</i>	<i>PTOA present (KL ≥2)</i>	<i>% OA</i>	<i>Joint fusion</i>	<i>% Joint fusion</i>
I	2	0	0	0	0
II	12	12	50	5	21
III	5	14	74	4	21
IV	0	3	100	1	33

PTOA: post-traumatic osteoarthritis; KL: Kellgren-Lawrence Scale

Table 4: Outcome scores across three categories of fracture energy (“low”, “intermediate,” and “high”). Scores are presented medians (min-max).

	<i>Low:</i> <i>14.1-17.9 J</i> <i>(n=16)</i>	<i>Intermediate:</i> <i>18.1-20.3 J</i> <i>(n=17)</i>	<i>High:</i> <i>20.5-26.2 J</i> <i>(n=15)</i>
VAS	6.0 (5.0-8.5) <i>p=0.0006</i>	3.5 (0.0-8.5) <i>p=0.2677</i>	6.0 (3.5-8.0) <i>p=0.0075</i>
SF-36 Physical	40.9 (30.5-60.6) <i>p=0.4221</i>	46.7 (27.8-56.6) <i>p=0.0369</i>	32.3 (16.4-33.7) <i>p=0.0041</i>
SF-36 Mental	60.4 (38.7-63.4) <i>p=0.2667</i>	54.4 (18.5-63.9) <i>p=0.8673</i>	52.7 (39.2-57.8) <i>p=0.9134</i>

VAS, visual analogue scale; SF-36, 36-Item Short Form Survey

Table 5: Outcome scores by development of PTOA. Scores are presented median (min-max).

	<i>PTOA present</i>	<i>PTOA absent</i>	<i>P value</i>
VAS	5.0 (0.0-8.5)	5.0 (1.5-8.5)	0.5465
SF-36P	33.7 (16.4-56.6)	45.8 (16.4-60.6)	0.0126
SF-36M	47.9 (36.8-57.8)	60.4 (18.5-63.9)	0.0042

PTOA, post-traumatic osteoarthritis; VAS, visual analogue scale; SF-36P, 36-Item Short Form Survey Physical Component; SF-36M, 36-Item Short Form Survey Mental Component

Table 6: Articular step off (mm) for fractures by KL Grade. Rho=0.25, p=0.0917

<i>KL Grade</i>	<i>Step off (mm)</i>
0	1.63 (1.13)
1	1.82 (1.17)
2	1.93 (0.87)
3	2.18 (1.01)
4	2.32 (1.14)

KL: Kellgren-Lawrence Scale

Figure 1

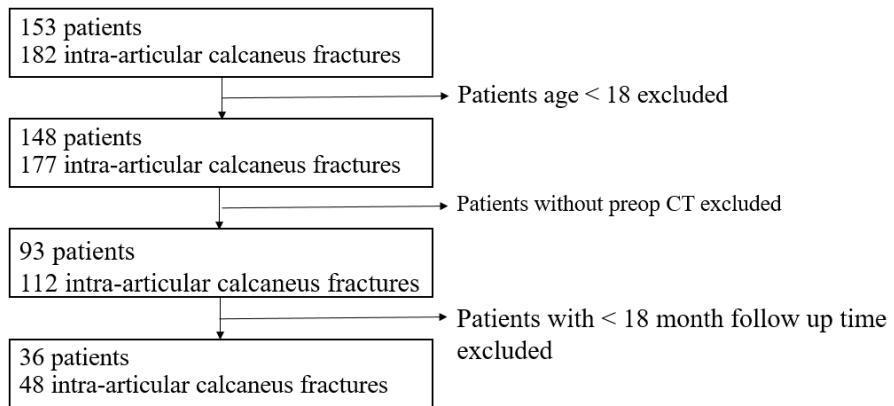


Figure 2

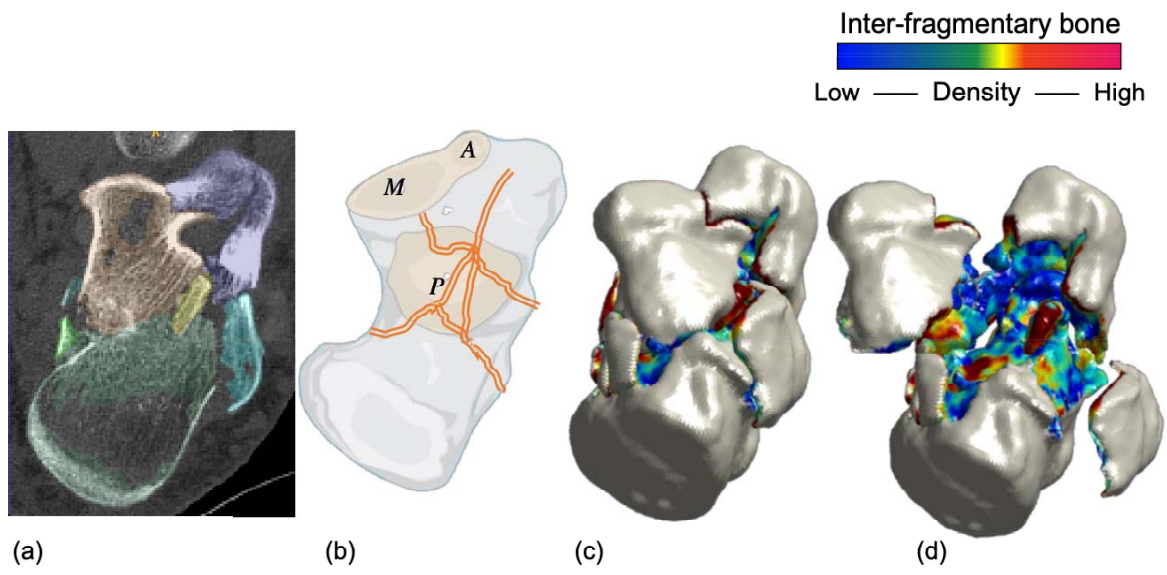


Figure 3

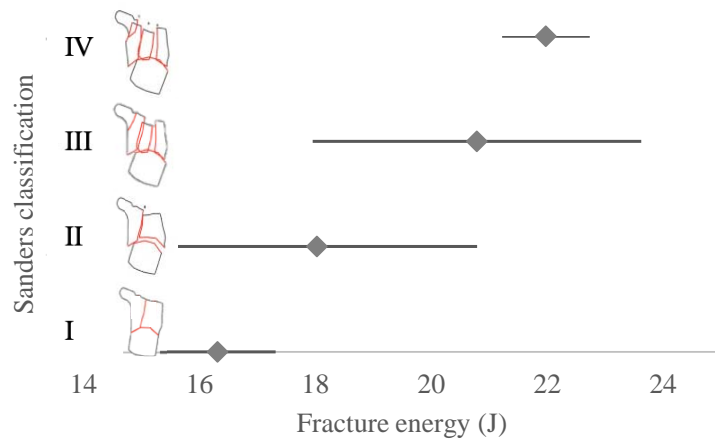
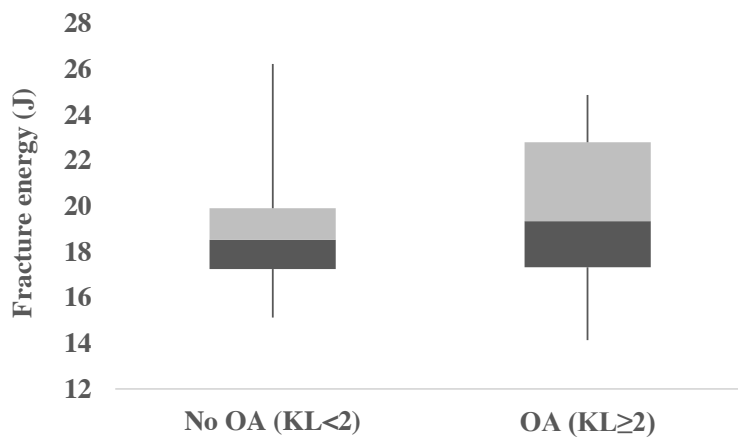


Figure 4



**A Universally Applicable, Objective CT-based Method for
Quantifying Articular Fracture Severity**

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Introduction

Articular fractures involving joints of the lower extremity are particularly devastating injuries, with from 25% to 74% of patients suffering them eventually developing post-traumatic osteoarthritis (PTOA) in the affected joint [1]. PTOA presents a tremendous burden both to the patients and for the economy, with an estimated \$12 billion annual cost[2]. Despite investments in new medicine and advances in surgical care over the past 50 years, the rates of PTOA following articular fractures have not substantially declined [3]. The reasons are multifactorial, but they most likely involve under-appreciated acute pathomechanical factors and associated biological processes. Elevated contact stress or altered kinematics due to imperfect reduction of the articular surface or joint malalignment are chronic pathomechanical factors affecting PTOA risk, while the severity and nature of the initial injury are acute factors. Much of the focus in treating these fractures has been on improving surgical reductions by using better fixation hardware and imaging, effectively aimed at addressing chronic factors. The failure to account for the acute fracture severity, in large part because of difficulties in reliably and objectively assessing it, may well explain the inability to positively decrease PTOA rates after these injuries.

Recent data suggest that there exists a fracture severity threshold above which joints predictably progress to PTOA, regardless of surgical treatment. Objective CT-based measures of fracture severity were successfully used to predict PTOA risk in fractures of the tibial pilon [4]. The origin of these measures was the clinical axiom that “the extent of bone, cartilage, and soft tissue damage is directly related to the energy imparted to these structures”[5]. Fracture mechanics is a well-established science based on the observation that energy is expended in the creation of new fracture surfaces. In the case of a brittle solid, this energy can be directly related to the amount of fracture-liberated surface area and the density of the material fractured. At the

high rates of loading seen in fracturing events, bone behaves as a brittle solid, and the fracture-liberated surface area and bone density can both be determined from CT scans [6, 7]. Relying upon these principles, Thomas et al. 2010 developed fracture severity assessment methods to identify this liberated surface area by using an intact contralateral limb as a datum for comparison. From the CT-based analysis, two distinct components of fracture severity that were estimated arose as being significant factors in PTOA risk: the energy of the fracturing event (i.e., the fracture energy) and the degree of articular comminution [4].

Unfortunately, the utility of the fracture severity assessment methods was limited by their reliance upon a CT scan of the intact contralateral limb that is not routinely available. Methods were later developed that obviated the need for a CT scan of the contralateral limb[4, 8], but they were specific to the distal tibia and therefore could only be utilized in the tibial pilon. The focus of this paper is to describe a more universally applicable, objective CT-based method that has been developed for quantifying articular fracture severity in any joint. Establishing the ability of these new methods to replicate measures arising from the previous studies and provide comparable prediction of PTOA risk was also a goal of this work.

Methods

The new method first involved segmenting CT scans of the fractured limbs to identify and separate bone fragments. Individual bone fragment volumes were identified using a semi-automated watershed transform-based algorithm implemented in MATLAB (The Mathworks, Natick, MA, USA).[9] Review by an experienced analyst ensured that surfaces identified by the semi-automated algorithm corresponded to inter-fragmentary boundaries (Figure 1). Discrepancies were corrected using a custom interface written in MATLAB.

These segmentations were then utilized to generate 3D surface models of the fractured bone for use in delineating intact and fractured surfaces so that the interfragmentary fracture-liberated area could be quantified (Figure 2). The 3D models were smoothed and decimated in Geomagic Design X (3DS Systems, Rock Hill, SC) for use in a surface classification algorithm. A Naïve Bayesian Classifier was trained to aid in separation of intact and fractured bone surfaces. Features used in training included the Hounsfield Unit intensities, the second derivative of the intensities, and the minimum, maximum, and Gaussian surface curvatures at each vertex. Finally, a graph cut was implemented to define the boundary between intact and fractured bone on each fragment (Figure 3). As part of this process, the subchondral bone surface was also identified. The outputs of this classification process were then used to expedite separation of intact and fractured bone with manual adjustment performed to finalize the fracture surface identification.

The CT Hounsfield Unit intensities were then sampled at each identified fractured face on the surface to estimate location-specific bone densities (Figure 3). Densities were determined from Hounsfield intensities through an established nonlinear relationship[10, 11]. The energy required to liberate fractured surfaces is related to the apparent density through a material constant, the strain energy release rate (J/m^2). From these relationships and the area of each sample face, an incremental fracture energy can be computed. When then summed over the entire fracture surface, this provide an estimate of the overall fracture energy.

The degree of articular comminution had previously been quantified as a ratio of fractured to intact bone surface area present within 1.5mm of the articular joint. In the new methodology, the measure of articular comminution was chosen based on knowledge of the distribution and progression of chondrocyte damage after articular fractures. Tochigi et al. 2011 found that initial chondrocyte death in articular fractures occurs preferentially along fracture edges and only later

progresses beyond [4]. Therefore, in an effort to meaningfully quantify articular comminution and the corresponding burden to joint health, the articular fracture edge length was selected in the new methods. Based on semantic information arising from the earlier surface classification algorithm, the articular fracture edge length is simply defined as the length of the intersection between subchondral and inter-fragmentary bone surfaces (Figure 3).

Once these new fracture severity assessment methods had been developed, we sought to determine how well the resulting measures agreed with those previously reported. The original fracture severity assessment methods had been used to study a group of twenty patients with isolated tibial pilon fractures (13 male, 7 female, ages from 20 to 64 years) selected to span a spectrum of severity [4]. Injuries ranged from partial articular to fully comminuted articular fractures (OTA type 43B2 to 43C3). Patients were followed for two years post-injury, and PTOA status at final follow-up was assessed from weight bearing radiographs using the Kellgren-Lawrence(KL) grading scale, a widely accepted radiographic arthrosis assessment instrument that has been shown to have good inter-observer reliability [12].

The fracture energies computed using the new methodology were compared to those using the existing methodology to evaluate how well they agreed. While not directly analogous, the measures of articular comminution computed by the two methods were also compared. The fracture energies and articular comminution measures computed by both methods were all linearly regressed as independent predictors of KL score. The ability for the new measures to predict PTOA development, defined as $KL \geq 2$ at final follow-up, was also compared to that of the original method in the 20 tibial pilon fractures.

Results

The fracture energies of the tibial pilon fractures previously computed and reported ranged from 5.2 to 27.2J, with a mean \pm standard deviation of 14.3 ± 7.8 J. Fracture energies computed using the new method ranged from 6.5 to 28.9J, with a mean \pm standard deviation of 15.6 ± 7.6 J. The amount of articular comminution previously reported ranged from 51 to 156% with a mean \pm standard deviation of 98 ± 29.3 %. The new measure of articular comminution, the articular fracture edge length, ranged from 72.1 to 257.1mm with a mean \pm standard deviation of 129.6 ± 51.5 mm.

There was strong agreement between the fracture energies computed with the two methods, with an R^2 correlation of 0.92 (Figure 4). The two fracture energies were further evaluated using a Bland-Altman difference plot to examine the distributions of the measurement (Figure 5). On average, there was a 1.2J bias toward higher fracture energy measured using the new methods. These data suggest that 95% of fracture energies computed using the new methods would be within ± 4.4 J of those computed using the original methods.

Both the fracture energies and articular comminution metrics computed using the two different methodologies were identified as highly significant predictors of PTOA risk, defined as a KL grade of ≥ 2 at final follow-up. For all measures, p-values were less than 0.002 (GMFE $p < 0.0001$; JSFE $p < 0.0001$; GMAC $p < 0.0006$; JSAC $p < 0.0018$).

Discussion

Traditionally, the severity of articular fractures is assessed using categorical fracture classifications. However, reliability and prognostic capability of such assessments have been questioned[13-16]. Shortcomings in these severity assessments are most prominent in sub-classifications that attempt to capture the degree of fracture comminution. Poor inter-rater reliabilities have been found with sub-classifications primarily because comminution does not

exist in discrete categories, but over a continuous spectrum[14, 15]. The present clinical gold standard for reproducible assessment of severity is rank ordering by expert raters, as they are able to directly compare cases over the continuous spectrum of injury. However, this approach is not objective, amenable to translation between patient series or across joints, and still fails to fully encompass the effects of initial severity on patient outcomes[16].

Beardsley et al. 2004[17] and Anderson et al. 2008[18] first introduced and advanced objective CT-based techniques for quantifying acute fracture severity. These techniques established the value of such metrics by first demonstrating agreement with subjective opinion of experienced orthopedic trauma surgeons.

Thomas et al. 2010[4] were the first to directly apply an objective CT-based quantification of acute fracture severity to a clinical population with clinical outcomes available. Their data provided evidence that measures of articular comminution and fracture energy are strong predictors of PTOA risk. The pathomechanical measures of acute fracture severity incorporated, fracture energy and articular comminution, were chosen to have direct physical meaning in any articular joint. The methods developed, however, did not readily lend themselves to extension to other joints, especially in the absence of a CT of the intact contralateral bone.

The purpose of the work reported in this paper was to develop a universally applicable CT-based methodology to objectively and quantitatively assess the severity of articular fractures in any joint. This work expands upon the prior studies establishing the efficacy of CT-derived measures of fracture energy and articular comminution as joint specific assessments of fracture severity in the tibial pilon. Both the original and the new methodology utilize pre-operative CT scans of the fractured limb, but the new methodology eliminates the need for an intact contralateral datum in computation of its severity measures. The newly developed methods

directly classify inter-fragmentary surfaces and enable location-specific Hounsfield intensities to be measured for a more robust and potentially more accurate approximation of fracture energy. The techniques described make the new methods directly applicable to fractures other than of the tibial pilon, requiring only a standard of care CT scan of the fractured joint.

The evaluation of the performance of the new methods in assessing fracture severity involved not only comparisons with results obtained using the original methods, but also against PTOA risk, in 20 patients with tibial pilon fractures. The fracture energy estimates computed by the two methods did not significantly differ; in the cases evaluated, the average difference in fracture energy was 1.2J with a 95% confidence interval of -3.2 to 5.6J. With respect to PTOA risk, the quantitative measures of fracture energy and articular comminution measures both showed moderate correlations with KL grade ($R^2 = 0.54$ and $R^2 = 0.34$, respectively), while in combination they explained 58% of the variance in KL grade. Even more significantly, the data are suggestive of a threshold above which the development of PTOA becomes highly likely. Thomas et al. 2010 were the first to report the existence of such a threshold, this time seen using a biologically grounded measure of cartilage damage through the estimation of chondrocyte death via measurement of the articular fracture edge length.

Objective quantitative assessments of fracture severity have important implications for future research in orthopedic trauma. These assessments possess significant prognostic utility for PTOA risk. This indicates that for articular fractures, the acute severity plays a larger role in determining patient outcomes than is currently appreciated and may provide a basis for better counseling of patients being treated. Future clinical studies should include these objective measures of fracture severity to more effectively evaluate differences in treatment groups, especially given recent trends toward acute complementary biological treatment.

The new methods represent a consequential and necessary advancement over the previous methods, by providing comparable predictive capabilities and being applicable for use in any articular fracture. Additionally, advancements in the semi-automated segmentation of CT scans and classification of fractured surfaces have substantially reduced analysis time from 8-10 hours per pilon fracture to less than 2 hours now per case.

There are nonetheless limitations in this study and the measurement techniques developed. Chronic pathomechanical factors, such as elevated contact stress from residual incongruity in the articular surface or malalignment of the joint, are not included in the methods. This may well be a moot point, however, as the acute fracture severity and quality of articular reduction are closely related [19]. Therefore, it is possible that aberrant contact stresses in the more severe fractures included in this study were the primary pathomechanical determinant of PTOA. Many other patient and surgical variables (e.g., biologic and anatomic variability) that may affect fracture behavior and healing were not included, either. Some fractures with significant impaction or bone volume loss due to comminution may also affect the fracture energy measurement as it assumes no bone volume is lost during fracture. This assumption is based on results from preliminary studies using these methods, which suggested very little volumetric loss of bone. Similarly, the articular fracture edge length may underestimate articular insult because it is measured only at the boundary of subchondral and inter-fragmentary bone surfaces. Therefore, comminution of bone resulting in fragments too small to accurately segment ($< \sim 20 \text{mm}^3$) is not fully captured. Finally, though the present average of 2 hours of analyst time per case is significantly reduced, it still poses a significant barrier to implementation of the methods in routine clinical practice. Though highly automated, bone fragment segmentation and separation still pose significant challenges that necessitate significant user intervention. Advancements in

clinically available CT-resolution and further application of machine learning techniques may be utilized to solve these problems in the future.

The primary objective of this research was to establish a novel, clinically relevant methodology to objectively assess and quantify articular fracture severity in any joint. This novel, universally applicable methodology offers new possibilities to enhance present clinical research paradigms. A dedicated analyst can now assess multiple cases per day, enabling objective control for the severity of injury over a continuous range for larger, multi-centered research studies. Building upon these developments, our group has now analyzed the fracture severity on over 300 articular fractures involving the distal radius, the acetabulum, the tibial plateau, the tibial pilon, and the calcaneus[20, 21]. Findings from these studies promise to provide new insights into the influence of fracture severity on PTOA risk in these devastating injuries, and they offer new opportunities to test new therapeutic biological treatments to alleviate the risk.

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Figure 1. Semi-automated identification of bone fragments from pre-operative CT imaging.

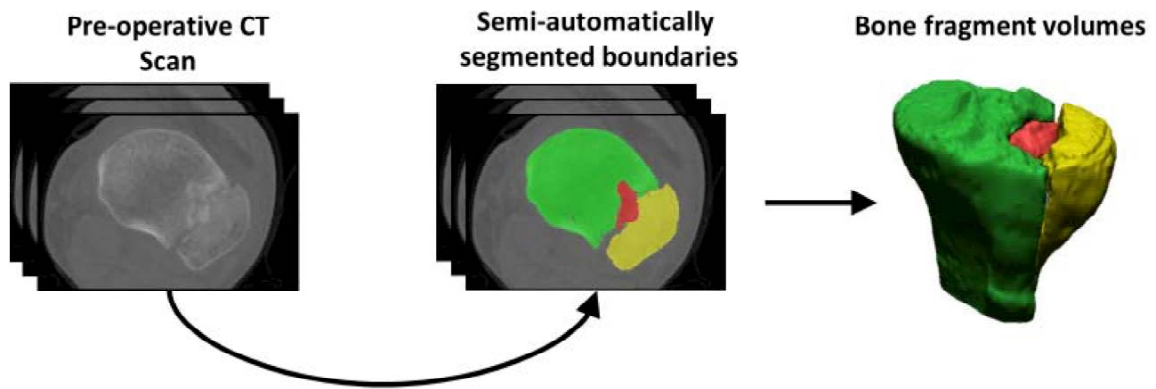


Figure 2. 3D surface models of the fractured bone for use in delineating intact and fractured surfaces so that the interfragmentary fracture-liberated area could be quantified

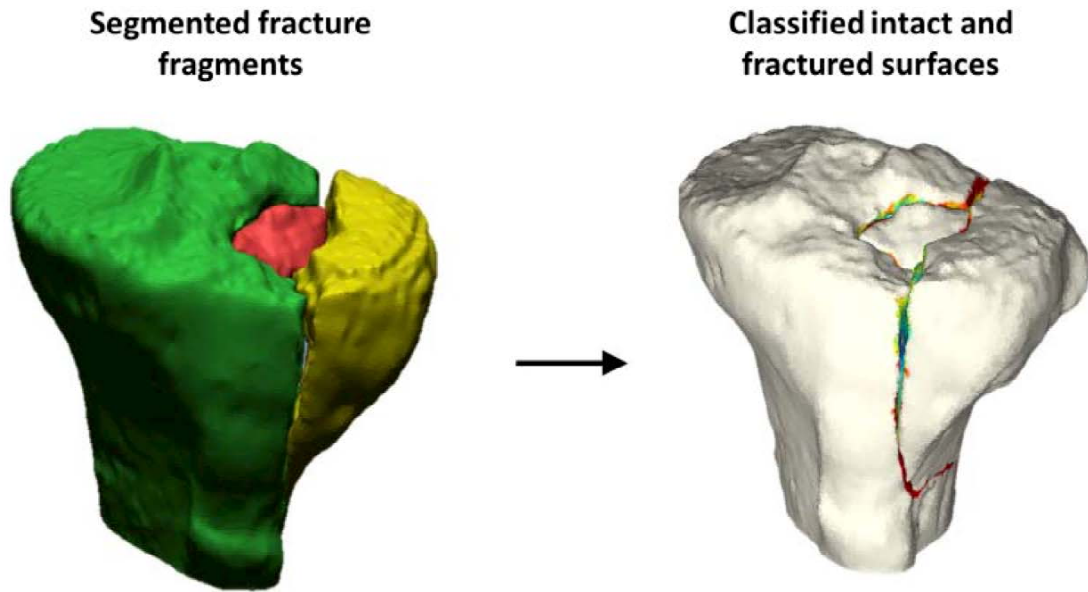


Figure 3. A graph cut was implemented to define the boundary between intact and fractured bone on each fragment so the fracture energy and articular fracture edge length could be computed.

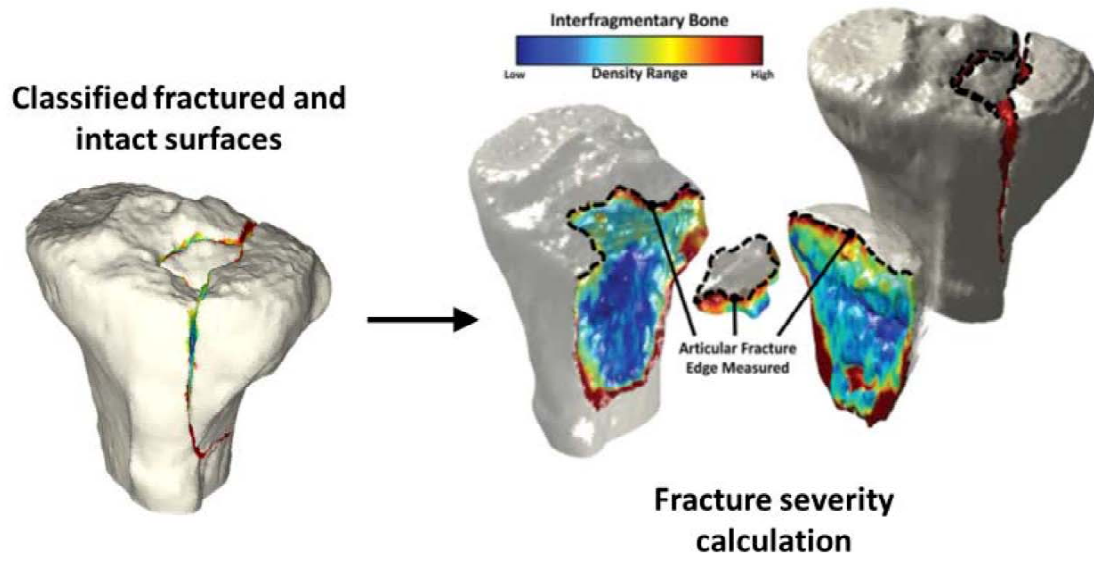


Figure 4. Correlation between the present fracture energy measure and the previously reported fracture energy measure.

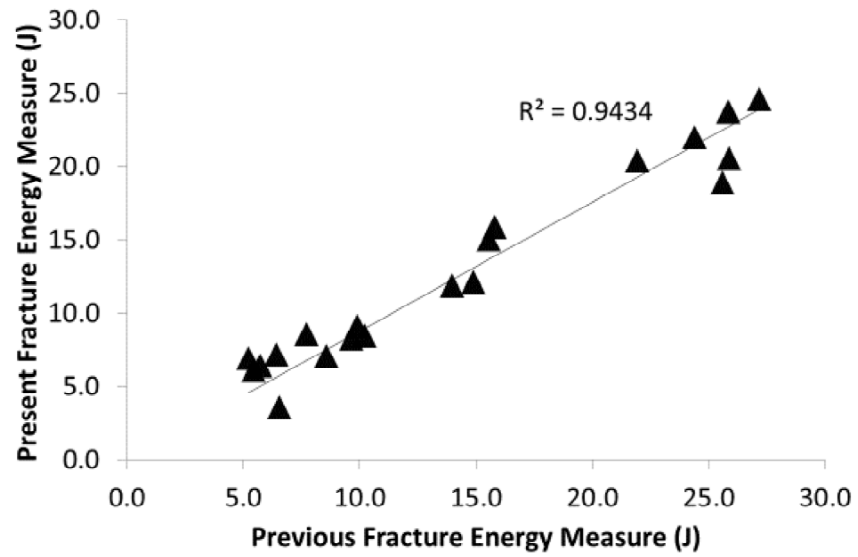
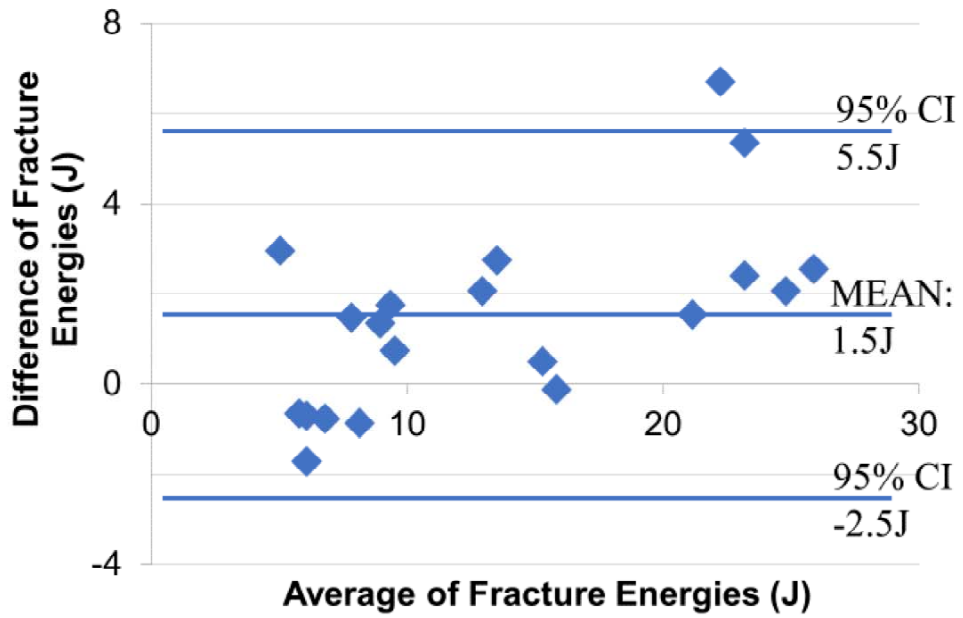


Figure 5. Bland-altman plot of fracture energies in the present and previously published fracture energy measure.



**Toward a Unifying Understanding of the Influence of Acute Fracture Severity
on Risk of Post-traumatic Osteoarthritis Following Intra-Articular Fractures**

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Introduction

The clinical management of displaced intra-articular fractures (IAFs) focuses primarily on the surgical reduction and stabilization of articular fragments. However, even in the best of hands, an IAF still frequently leads to disabling post-traumatic osteoarthritis (PTOA). Across joints of the upper and lower extremities, the incidence of PTOA remains stubbornly unchanged despite decades of improvements in technology and surgical management [1]. There are two broad theories regarding the mechanical origins of PTOA development that may help to explain this finding. The first is that following surgical IAF reduction, residual incongruities lead to changes in the joint's mechanical environment that are deleterious to cartilage health. The second is that the initial fracturing event damages the joint beyond its capacity to recover. Though both undoubtedly contribute, unaccounted for variation in the acute fracture severity may better explain the lack of a decline in PTOA rates following IAFs despite ostensibly improved surgical treatment. We hypothesize that it is the acute fracture severity, along with engendered biological responses, that contributes most significantly to PTOA risk in these joints.

The PTOA risk after IAF is widely held to relate to the fracture type and its severity, even across different surgical treatment approaches [2-4]. However, there are no clinically available methods to objectively assess fracture severity. Instead, fracture severity assessment relies upon joint-specific categorical classification systems that have poor inter-observer reliability [5, 6]. As such, they fail to provide a consistent contextual indication of fracture severity as it relates to PTOA risk across the different articular joints. To remedy these shortcomings, novel CT-based analysis methods have previously been developed to objectively quantify IAF severity [7-10]. The methods are based upon the principle that mechanical energy is required to create new free surface area when fracturing a brittle solid, and that the amount of energy required is directly related to the amount of *de novo* surface area. This approach was originally developed using laboratory models (first, a dense polyether-urethane foam bone surrogate material, [9, 10] then in bovine bone segments [8]) and subsequently extended it to use in human clinical

cases[7]. Over the past decade, these techniques have been further developed to enable larger-scale study of fracture severity in the clinical setting [7-9]. The objective of the present study was to leverage these new assessment capabilities toward a unifying understanding of the influence of acute fracture severity on PTOA risk following IAFs across a variety of articular joints.

Methods

We enrolled 262 patients having sustained IAFs in this multi-institutional level III diagnostic study. Patients were selected for having pre-operative CT scans available for IAFs of the distal radius (n=22), acetabulum (n=22), proximal tibia (n=88), distal tibia (n=82), and calcaneus (n=48). An Institutional Review Board approved use of the imaging and patient data collected in the course of their standard-of care clinical treatment.

Fracture severity was analyzed for all fractures included in the study using previously validated, objective analysis methods working from pre-operative CT scans [11-13]. The analysis methods quantify the energy involved in creating a fracture (the fracture energy) using principles from fracture mechanics.

Custom written MATLAB software was used first to segment bone fragments from CT scans and then to automatically classify the *de novo* fracture-liberated surface area based upon CT Hounsfield intensities and local geometric features (surface roughness, curvature, etc.). The segmentation and classification results were manually verified and corrected as needed by an expert analyst. Bone densities were then estimated in the fractured regions from the Hounsfield intensities at each CT scan voxel using previously established relationships. These location-specific bone densities were used to scale the fracture liberated surface areas by density-dependent strain energy release rates to determine the fracture energy for each case.

When axial fracturing impacts are delivered to a joint, energy transfer is distributed over the articular surface through the contact area. To enable comparisons of the fracture energies

across different joints, we normalized to characteristic joint-specific contact areas. We queried the peer-reviewed literature for generally accepted averages of the relevant contact areas (Table 1). In lieu of appropriate duration longer-term clinical follow-up data for each of these patients, we again turned to the published literature to find average rates of PTOA development for each of the joints as a point of comparison. For consistency across the studies, we defined PTOA as being present in joints when the Kellgren-Lawrence radiographic grade [3] was greater than or equal to 2. A summary of the PTOA rates for each joint and the source papers can be found in Table 1.

Finally, to explore how acute fracture severity influences PTOA risk after IAF, we first examined correlations between the computed fracture energies and published PTOA rates. Then an additional data analysis step involved likewise examining correlations between contact area-normalized fracture energies and PTOA rates.

Results

The fracture energies measured for all cases analyzed ranged from 0.9 to 38 Joules (J). The range of fracture energies for calcaneal fractures was 14.2 to 26.2J, for distal tibial fractures it was 0.9 to 38J, for proximal tibial fractures it was 3.2 to 33.2J, for acetabular fractures it was 4.6 to 32.8J, and for distal radial fractures it was 2.8 to 9.0J. The fracture energies (mean \pm standard deviation) were 19.3 ± 3.1 J for calcaneal fractures, 15.3 ± 7.3 J for distal tibia fractures, 13.1 ± 6.5 J for proximal tibia fractures, 18.0 ± 8.2 J for acetabular fractures, and 4.9 ± 1.8 J for distal radius fractures. The distribution of energies was highly dissimilar between a number of these groups with no overlap whatsoever between the calcaneal and distal radius fractures (Figure 1).

The contact area-normalized fracture energies ranged from 0.14 to 8.90 J/cm² for all cases. The range of contact area-normalized fracture energies for calcaneal fractures was 4.80 to 8.90 J/cm², for distal tibial fractures it was 0.21 to 4.66 J/cm², for proximal tibial fractures it was 0.28 to 2.92 J/cm², for acetabular fractures it was 0.22 to 1.58J/cm², and for distal radial fractures it

was 1.38 to 4.47 J/cm². The contact area-normalized fracture energies (mean ± standard deviation) were 6.55±1.04 J/cm² for calcaneal fractures, 1.77±1.15 J/cm² for distal tibia fractures, 1.16±0.57 J/cm² for proximal tibial fractures, 0.87±0.39 J/cm² for acetabular fractures, and 2.41±0.87 J/cm² for distal radius fractures. There was a trend toward decreasing energy in joints going from distal to proximal in the lower extremity with distal radial fractures having energies in the middle of the range (Figure 2).

Qualitatively, high energy fractures in all five joints shared similar characteristics having similar size, number, and dispersion of fragments (Figure 3). However, they did not demonstrate such similarities for the lower end of their spectrum. When comparing fractures of similar energy across joints, there were perceptible differences in the appearance of fractures. An 8J fracture in the ankle can appear relatively minor while an 8J fracture of the distal radius can have a highly comminuted joint space with large diaphyseal extensions. Comparing joints with similar contact area-normalized fracture energies showed more consistent appearance across joints. A 4.29 J/cm² fracture of the distal radius is similarly comminuted with diaphyseal extension as is a 4.19 J/cm² fractures of the distal tibia (Figure 4).

The computed fracture energies showed no correlation whatsoever with the published rates of PTOA across the joints studied (Figure 5). However, there was a highly significant correlation between contact area-normalized fracture energies and the rates of PTOA (Figure 6).

Discussion

This study sought to understand the influence of acute fracture severity on PTOA risk following IAFs across a variety of articular joints. The hypothesis that acute fracture severity contributes significantly to the risk of PTOA development was supported by these data. There was a strong correlation between the fracture energy per unit contact area, obtained from pre-operative data, and PTOA rates across 5 different joints without controlling for any operative factors. This elucidates a potential reason for the disconnect between advances in fracture

management and the lack of improvement observed in PTOA prevention after IAFs. Acute biological damage caused by fracture is not effectively treated but appears to be a significant contributor to PTOA risk. As ~85% of the variance in PTOA rates appears to be due to the initial severity, novel biological interventions may reduce PTOA development substantially.

Though PTOA is a known sequela of acute IAF, the exact mechanism and the contributions of acute injury to its development have remained unclear. In 2011, Tochigi et al made two major discoveries. Upon examination of debrided fragments containing cartilage from calcaneal fractures, they found significantly lower chondrocyte viability near fracture edges. Interestingly, they also found that chondrocyte death propagated from these fracture sites over the next several days [14]. This discovery is important because it demonstrates that acute damage likely has a long-term effect on cartilage health through decellularization of the tissue and that the acute effects of the injury progress after surgical intervention. From these findings, one might expect joints with more fracture edges to report higher rates of injury severity, however, a 2017 study by Dibbern et al found the opposite. They found that tibial plateau fractures had significantly higher fracture edge lengths than pilon fractures, despite plateaus reporting PTOA rates half those found in pilons[12]. To explain this finding, they suggested that differences in the impact tolerance of some joints could be due in part to differences in the size of the articular surface. Distributing the impact over a larger area would effectively lessen the magnitude of the injurious event per unit area, like contact stress is reduced by increasing contact area. For our study, to approximate this effect, the contact area was used to scale fracture energy by the area through which it could be transferred.

Fracture energy scaled by contact area is appealing in the context of assessing cartilage and joint damage. The distribution of the energy over that joint, now quantified by the scaled fracture energy, gives further insight into the severity of damage in a consistent and objective manner. The joints studied herein differ significantly in bony morphology, cartilage thickness, the surrounding anatomy, loading conditions, reconstruction difficulty, and injury patterns. However,

the results suggest that 85% of variance in PTOA rates between them may be due to the acute fracture severity.

This elucidates a potential reason for the disconnect between advances in fracture management and the lack of improvement observed in PTOA prevention. Acute biological damage caused by fracture is not meaningfully treated presently but appears to be a significant contributor to PTOA development. It likely manifests in a consistent manner across joints, but over an extended period of time as the effects of cartilage decellularization become realized when the matrix is not maintained. The fact that the decellularization process occurs over several days presents an exciting opportunity for intervention. As >85% of the variance in PTOA rates may be due to the initial severity, novel biological interventions may reduce PTOA development more substantially than previously estimated. It also suggests that less invasive surgical techniques may be preferred, especially when paired with interventions that can maintain chondrocyte viability in fractured joints.

Among the limitations of this study, the patients for whom fracture energies were computed were not all followed clinically. Therefore, rates of OA represent literature values derived from multiple patient populations. Similarly, PTOA was defined radiographically by the KL radiographic grade for studies that did not report OA development. However, the KL scale was not designed to consider symptoms when defining OA, so the relationships in this study represent radiographic, not necessarily symptomatic, OA. Finally, to be included in the study, CT scans had to be obtained during a standard of care protocol. As obtaining a CT scan does not necessarily fall under the standard of care for more minor fractures, it is possible the energy ranges are skewed toward the higher end and may not capture lower energy fractures.

Conclusion

The results of this multi-center study suggest that there is a strong correlation between PTOA risk and the severity of the initial injury for IAFs, independent of surgical management

and consistent across joints from both the upper and lower extremity. This offers a potential explanation for why PTOA rates have remained unchanged despite decades of improvement in surgical management. To address these issues, a shift in treatment paradigms to address acute joint damage may be required. Novel biologic interventions may become as important as reconstructive surgeries as focus shifts toward treatment of the acute biological damage. This study is the first to objectively compare the contribution of acute injury severity across different joints throughout the body. The results suggest that acute fracture severity may, in large part, explain why high PTOA rates persist after intra-articular fractures.

Acknowledgments

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Table 1: PTOA rates and Contact Areas in the Upper and Lower Extremity[1, 15-36]

	PTOA Rates	Contact Area (cm ²)
Calcaneus	87.5±4.5 (83-92%)	2.95
Distal Tibia	57.8±16.0 (32-75%)	6.16
Proximal Tibia	33.5±10.5 (23-44%)	11.35
Acetabulum	24.3±11.0 (11-38%)	20.74
Distal radius	44.5±20.5 (24-65%)	2.01

Figure 1. The distribution of energies for calcaneal, distal tibial, proximal tibial, acetabular, and distal radial fractures.

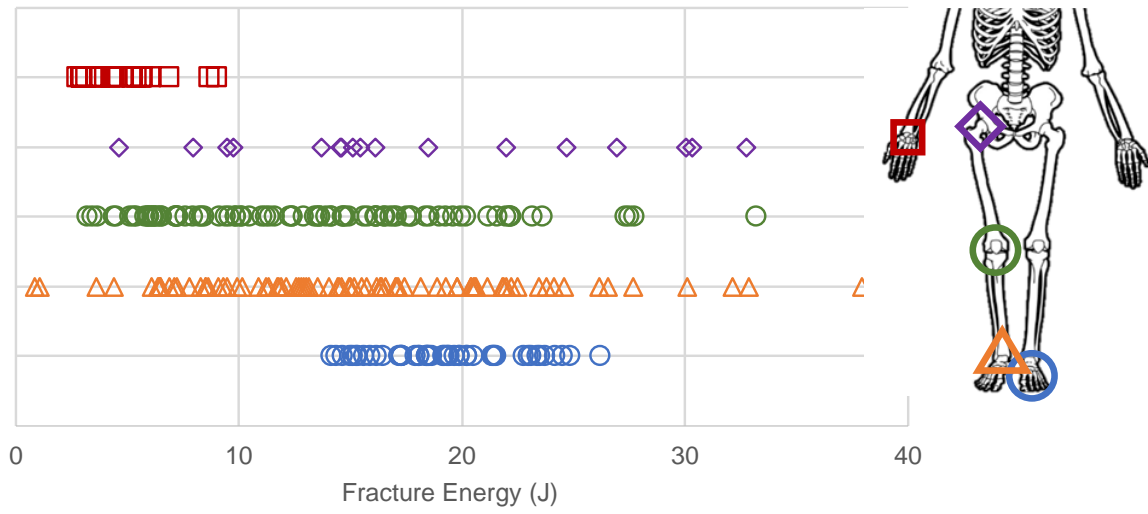


Figure 2. The distribution of energies for calcaneal, distal tibial, proximal tibial, acetabular, and distal radial fractures scaled by the average contact area for each joint.

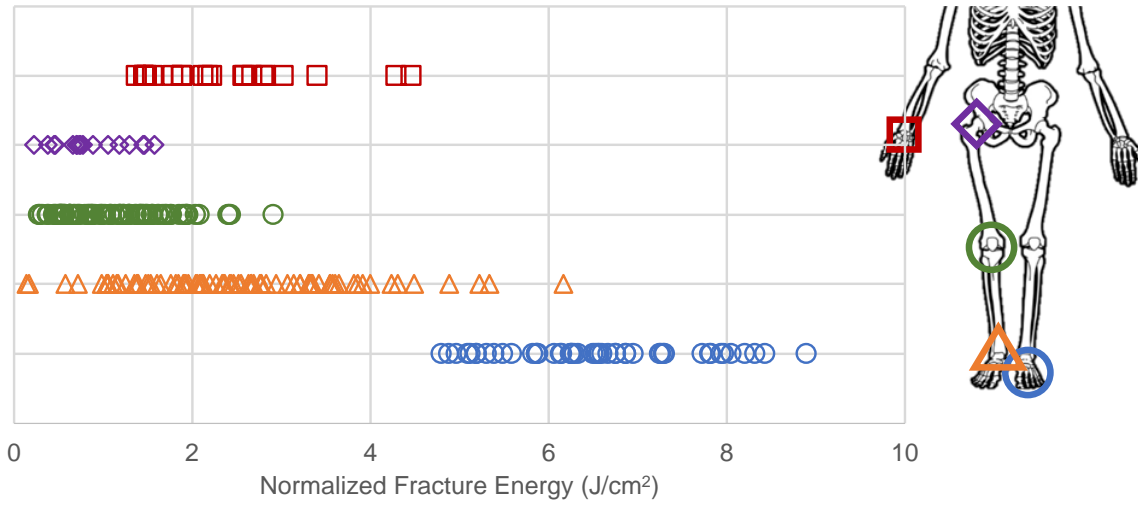


Figure 3. High energy fractures have similar characteristics across joints with many fragments, significant comminution, and disruption of the articular surface.

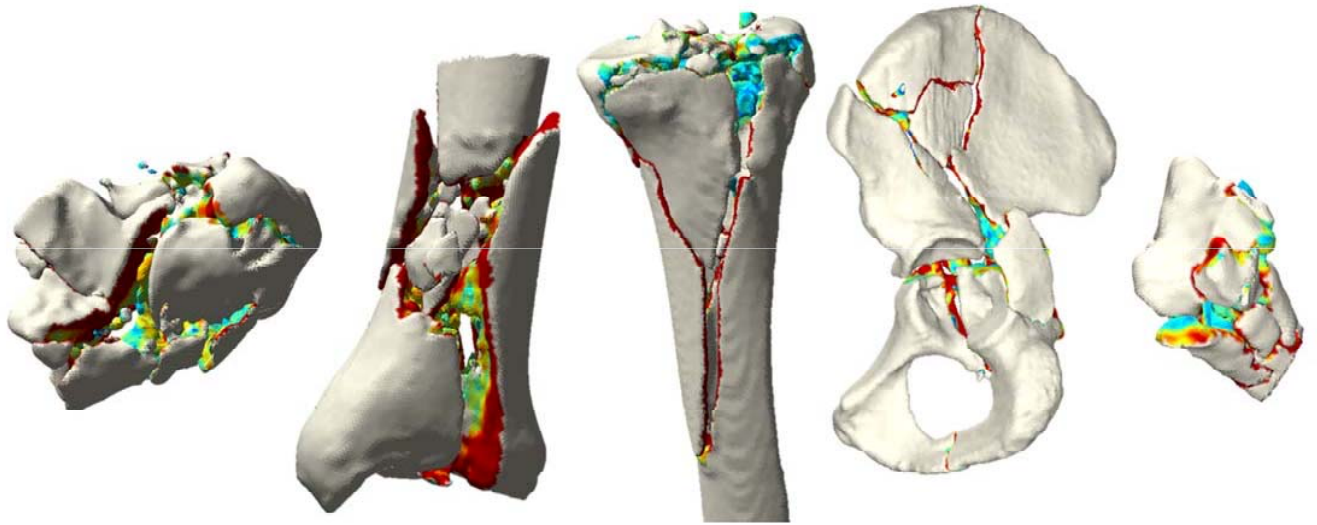


Figure 4. A 4.29 J/cm^2 fracture of the distal radius and a 4.19 J/cm^2 fracture of the distal tibia. Similar scaled fracture energy values tend to have visually similar degrees of damage.

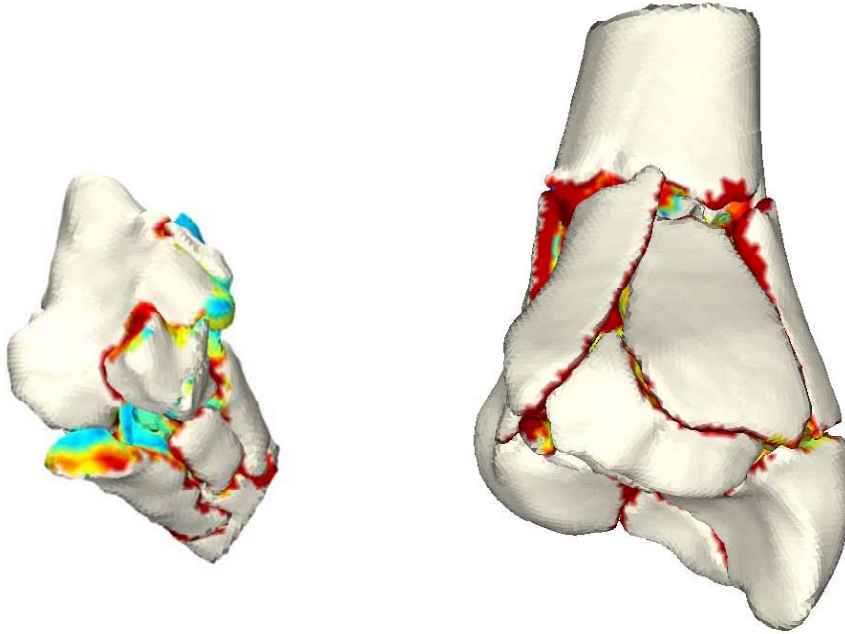


Figure 5. Fracture energies do not correlate with published rates of PTOA across the joints studied.

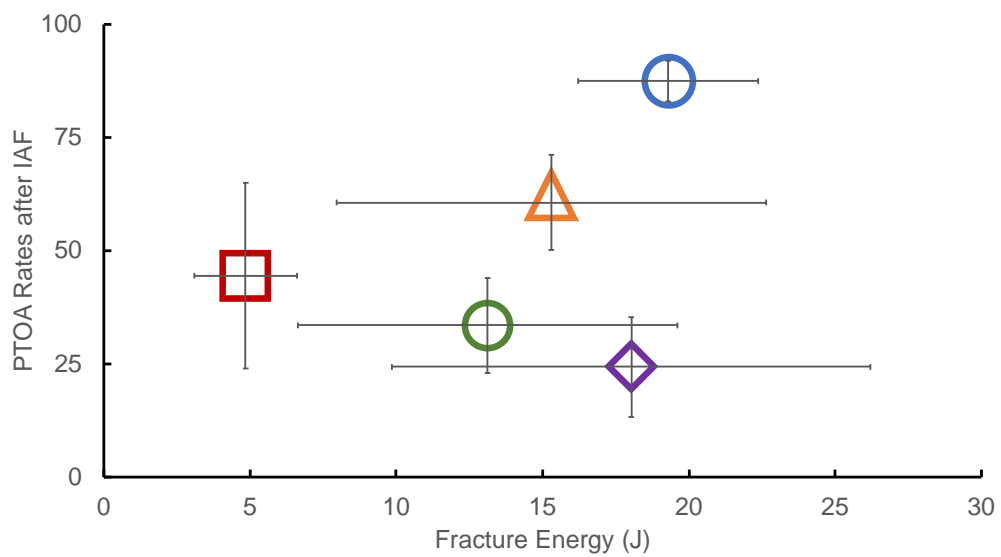
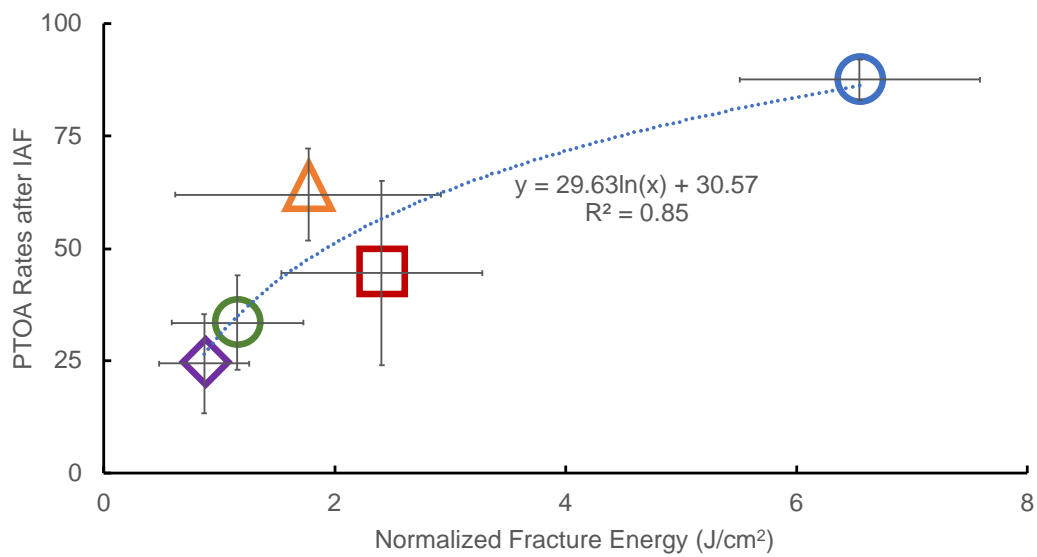


Figure 6. Area-normalized fracture energies have a highly significant correlation with rates of PTOA.



Elevated Joint Contact Stress is Associated with Radiographic Measures of Osteoarthritis in Operatively Treated Acetabular Fractures at Two Years

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Introduction

Despite improvements in fixation strategies over the past 4 decades, rates of post-traumatic osteoarthritis (PTOA) following acetabular fracture have remained constant[1]. Over 25% of patients presenting with an acetabular fracture will develop PTOA[1, 2]. Surgical treatment of these fractures focuses on restoring alignment, joint stability, and articular surface congruity. More than for any other joint, in acetabular fractures the development of PTOA is believed to be highly correlated with the quality of reduction[2-7]. Historically, fractures reduced within 1 mm of congruity have yielded superior clinical results when compared to reductions greater than 1 mm[5].

Malreduced fractures that do not achieve stability and congruity result in elevated contact stresses [8-12]. Prolonged exposure to these elevated contact stresses has been proposed as a mechanism for the mechanical degeneration to PTOA characteristic of articular fractures[10-12]. Studies in the ankle have demonstrated the predictive power of elevated contact stress in PTOA development[10-12]. However, the ability to assess reduction quality by performing contact stress assessment has not been feasible from clinically available CT scans until recently. Studies by Kern (2015) and Townsend (2018) established methods to use post-operative CT imaging to estimate contact stresses in articular fractures[11, 13]. These methods employ discrete element analysis (DEA), a computationally efficient method for estimating contact stresses that enables study of larger cohorts of patient-specific contact stresses. Though DEA has the potential to be implemented clinically, its utility in the context of evaluating acetabular fracture reduction has yet to be established. Therefore, the purpose of this study was to determine if elevated joint contact stress after fixation of acetabular fracture is associated with PTOA development at 2-year follow-up.

Methods

After obtaining Institutional Review Board (IRB) approval, a series of 75 patients at a single institution who had undergone operative fixation of acetabular fractures between 2004 and 2016 were identified for having pre-operative and post-operative CT scans. Patients were excluded from study for

having less than two-year radiographic follow-up, being under the age of 18 at the time of surgery, undergoing arthroplasty within the same hospital admission, or if they had associated femoral head fracture. Twenty-four patients declined to participate or were unreachable. Ten patients had undergone surgery within the past two years and thus did not have 2-year radiographic follow-up. One patient was 17 at the time of surgery. Of the remaining 40 patients, a total of 23 patients had adequate imaging and follow-up available for analysis.

Radiographs obtained at a minimum of two years were evaluated for arthritic changes by two independent evaluators. Each evaluator assigned a Tönnis grade to each hip using the modified Tönnis grading description scale [14]. When there was disagreement between observers, an arbitrator (MW) reviewed the studies and determined Tönnis grade. Patients having Tönnis grades 0 and 1 were included in the no PTOA group and Tönnis grades 2 and 3 were included in the PTOA group. Those patients who went on to total hip arthroplasty or femoral head resection prior to two year follow up were considered as Tönnis grade 3 equivalents for radiographic purposes.

Femoral and pelvic geometries for each patient were extracted from post-operative CT scans using a semi-automated watershed-based algorithm (Figure 1). Errors in the automated surface detection and separation protocol were manually corrected, and triangulated surface models of the anatomy were generated and smoothed (Geomagic Design X software, 3D Systems Inc., Rock Hill SC). Articular surfaces were approximated by projecting the acetabular and femoral subchondral surfaces a uniform distance of 1mm then subsequently smoothing the projected surfaces toward sphericity using a custom iterative smoothing algorithm [13]. The resulting approximations of the chondral geometries have been previously shown to yield accurate contact stress computations, even from fractured surfaces.

The models were aligned to the hip joint coordinate system defined by Bergmann et. al. (2001) based on patient-specific anatomic landmarks on the bone surface models[15]. DEA was used to compute contact stress over an entire gait cycle for each case (Figure 2). Boundary conditions for forces and rotations were based on patient-specific body weights and were defined by the Bergmann et. al. study (2001) from instrumented total-hips [15]. The stance phase of gait was discretized into 13 quasi-static

time steps to facilitate direct comparison of the resulting contact stress distributions (Figure 3). Forces were applied to the femur and directed toward the hip as dictated by the Bergmann data. Cartilage was assigned isotropic linear-elastic material properties ($E=8\text{MPa}$, $\nu=0.42$).

Cases were evaluated for maximum contact stress over the course of the gait cycle. An unpaired t-test was used to compare results between the no PTOA and PTOA groups. Results were also compared against 10 normal hips analyzed in the same manner during a previous study.

Results

A total of 23 patients (15 developed OA and 8 did not) and 10 healthy volunteers (serving as normal controls) were included in the final analysis. The average age of the patients was 40 ± 16.6 years at the time of surgery (42.5 ± 16.6 years in the OA group and 34.6 ± 15.1 years for the no OA group, $p=0.32$), and the average age of the controls was 34.6 ± 8.7 years ($p=0.34$). The average BMI was 29.9 ± 6.0 for the patients (29.5 ± 6.7 in the OA group and 30.8 ± 4.0 in the no OA group, $p=0.66$) and 35.0 ± 7.2 for the controls ($p=0.07$). There were 19 males and 4 females in the patient group (2 males and 17 females in the OA group) and 6 males and 4 females in the control group.

Qualitatively, the contact stress distributions in the control hips gradually varied over the surface. For the fractured hips, particularly those in the PTOA group, there were much more focal contact stress elevations that varied in location over the gait cycle (Figure 4), attributable to residual local articular surface incongruities.

The hips from healthy volunteers were exposed to an average maximum contact stress of 7.4 ± 2.0 MPa (mean \pm standard deviation). Hips from patients with acetabular fractures experienced an average maximum contact stress of 10.9 ± 3.4 MPa. Patients that developed PTOA had significantly higher maximum contact stresses in their hips than patients that did not (12.0 ± 3.8 MPa vs. 8.8 ± 0.7 MPa; $p=0.008$). Patients that developed PTOA also had significantly higher maximum contact stresses than did subjects in the control group ($p<0.001$), while there was no significant difference in maximum contact stresses between the controls and the patients who did not develop PTOA ($p=0.068$). Over the course of

the stance phase of gait, the PTOA group had higher maximum contact stress than the patients that didn't develop PTOA and the normal controls. The fracture patients that didn't develop PTOA also had consistently higher maximum contact stress than the normal control group (Figure 5).

Discussion

Acetabular fracture patients who developed PTOA had significantly higher contact stresses than both patients that did not develop PTOA and the normal controls. These results support the conclusion that exposure to chronically elevated contact stress in the hip after acetabular fracture leads to the development of post-traumatic osteoarthritis. Across the stance phase of gait, the average maximum contact stresses were higher for the patients that developed PTOA compared to the patients who did not develop PTOA and the normal controls. The differences were not significant between the PTOA and no PTOA groups across most of the gait cycle as there was a wide variance in the maximum contact stress at each time point for the fractured cases. This is likely due to anatomic differences and irregularities resulting from the fracture leading to peak contact stresses occurring at different points in the gait cycle. If we consider the peak maximum contact stress across the entire gait cycle, differences in the groups become more apparent (Figure 7). There appears to be a threshold around 11 MPA above which patients predictably progress to PTOA. Interestingly, this barely exceeds the highest maximum contact stress seen in the normal control group, indicating that even slight perturbations in the joint surface from normal in some cases may portend degeneration. However, in our data nearly half of the patients that developed PTOA (7/15) would be missed by this threshold, demonstrating the multifaceted nature of PTOA. These patients may have incurred irreparable damage from the initial fracture, have diminished regenerative capacity, or be predisposed to its development by a number of other factors that led to degeneration of their articular cartilage, despite a comparatively normal mechanical environment.

Selection bias is a limitation of this study. During the study period, post-operative CT scans were not routinely collected after fixation of acetabular fractures. Patients were selected from a consecutive series to identify cases with a post-operative scan. This most likely led to a higher incidence of more complex

cases, which is reflected in our high rate of conversion to total hip arthroplasty. This small series also includes a variety of fracture patterns, so it is not possible to draw conclusions about post-operative assessment of individual fractures patterns, such as posterior wall, transverse, or column fractures. These different patterns of acetabular fracture have varying levels of severity that also contributes significantly to the development of PTOA. Our primary outcome was PTOA measured using Tönnis grade. There are varying levels of reliability using this measurement for hip PTOA. To compensate for disagreement in scores an arbiter was required determine the grade of PTOA. More objective measures of PTOA need to be used to quantify levels of joint degeneration.

Contact stress calculated using discrete element analysis has been shown in this study to predict development of PTOA. This provides us with an objective tool to predict joint mechanics after articular fracture. This tool can be used to predict outcomes of an individual patient that underwent operative fixation of an acetabular fracture. Pre-operatively, DEA could be used as an efficient technique to determine if a patient would benefit from fixation of acetabular fractures. As we investigate clinical interventions to prevent PTOA after articular fracture it is important to have objective measures of contact stress. Future investigations will use this tool to determine how fracture pattern impacts contact stress in a larger series of patients.

Conclusions

PTOA is the most common complication following acetabular fractures, but the rate of PTOA development after repair has remained stagnant over the years. The results of this study support the assertion that the onset of PTOA is mediated by elevated contact stress. Specifically, that maximum contact stress at any point in a gait cycle is associated with PTOA at 2-year follow-up. Prior work has attempted to interrogate the mechanical environment of the joint by assessing surrogates of contact stress like step-off and gapping. Though recent studies have demonstrated the utility of CT scans in detecting residual step-off, gapping, and displacement following ORIF, these measurements are simply surrogates to assessment of contact stress. The methods developed in this work enable more precise and objective

determination of the quality of reduction in acetabular fractures. DEA can quantify the mechanical impact of imperfect reduction via the calculation of contact stress elevations throughout the articular surface. By identifying hips likely to degenerate due to a high level of residual incongruity, DEA-contact stress analysis may provide early prediction of joint failure and subsequent conversion to total hip arthroplasty.

Acknowledgments

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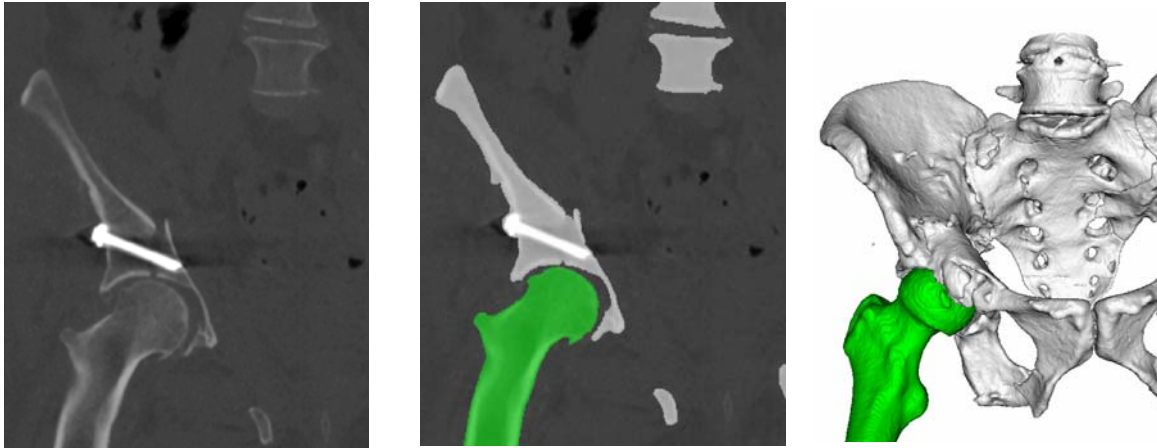
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Figure 1. Patient-specific 3D models of the hip were generated from post-operative CT scans of the surgically reduced acetabular fractures.

— 3D model generation from post-op CT —



post-op CT data \implies segmentation \implies 3D model

Figure 2. The contact stress distributions were computationally estimated using acetabular DEA models as depicted here. The femoral and acetabular subchondral bone surfaces are modeled as rigid bodies with a series of linear springs arrayed across the projected articular cartilage surfaces where contact is detected.

Acetabular DEA

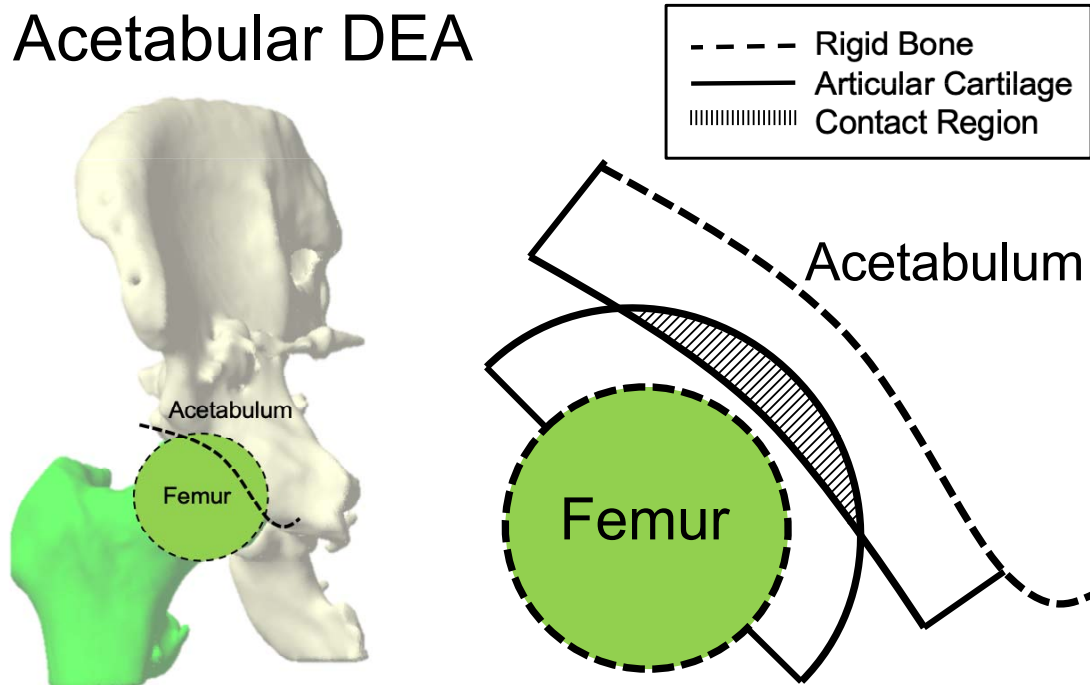


Figure 3. A series of 13 static loaded poses were simulated, with loads scaled to patient body weight, working from instrumented total hip data publicly available from Bergmann et al.

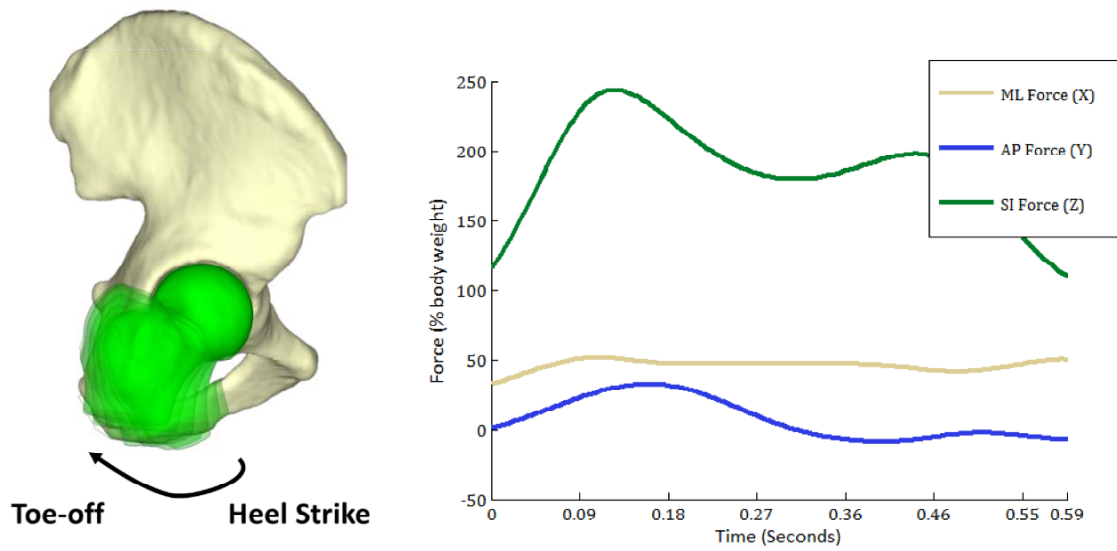


Figure 4. Contact stress distributions are computed at each of the 13 loaded poses to replicate the entire stance phase of gait.

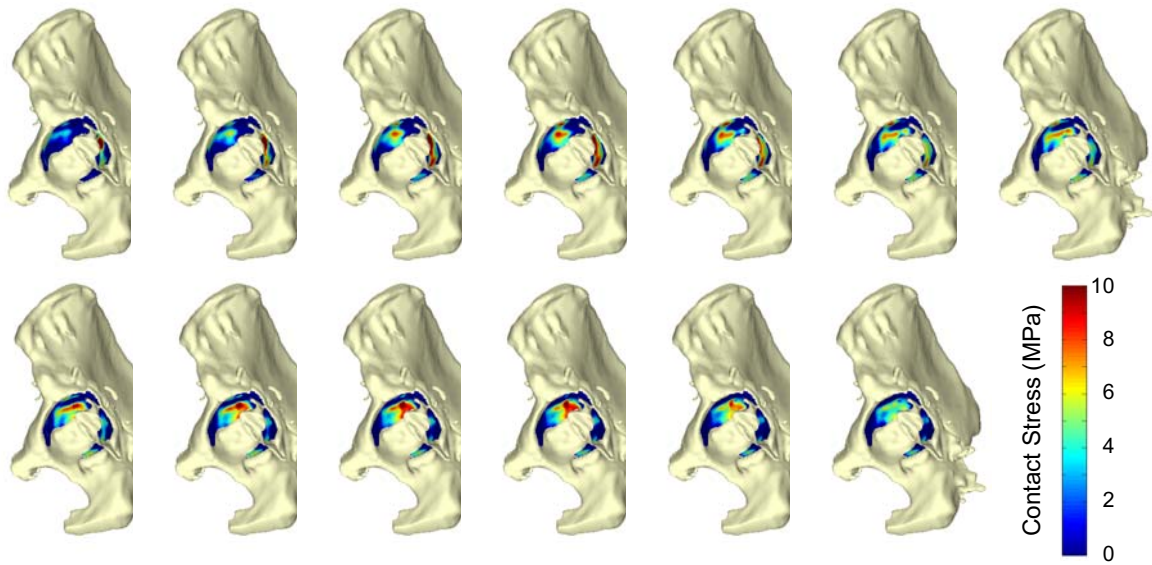


Figure 5. Over the entire stance phase of gait, the maximum contact stress in the OA group is higher than the no OA patients and normal hips.

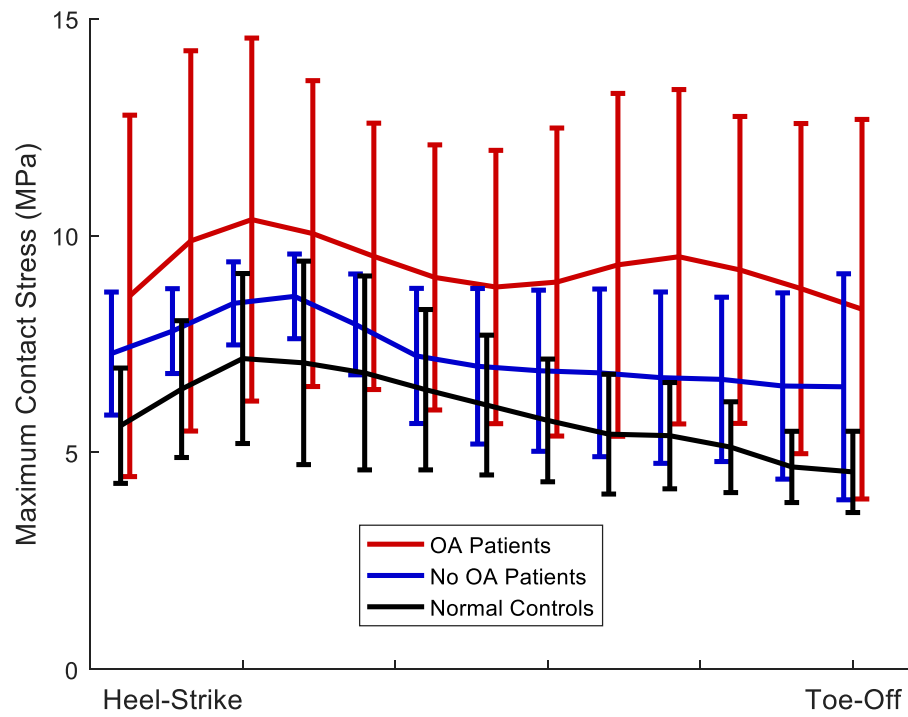


Figure 6. The contact stress distributions for the patients who had developed PTOA at two years after surgery were substantially more focal and had significantly higher peak values.

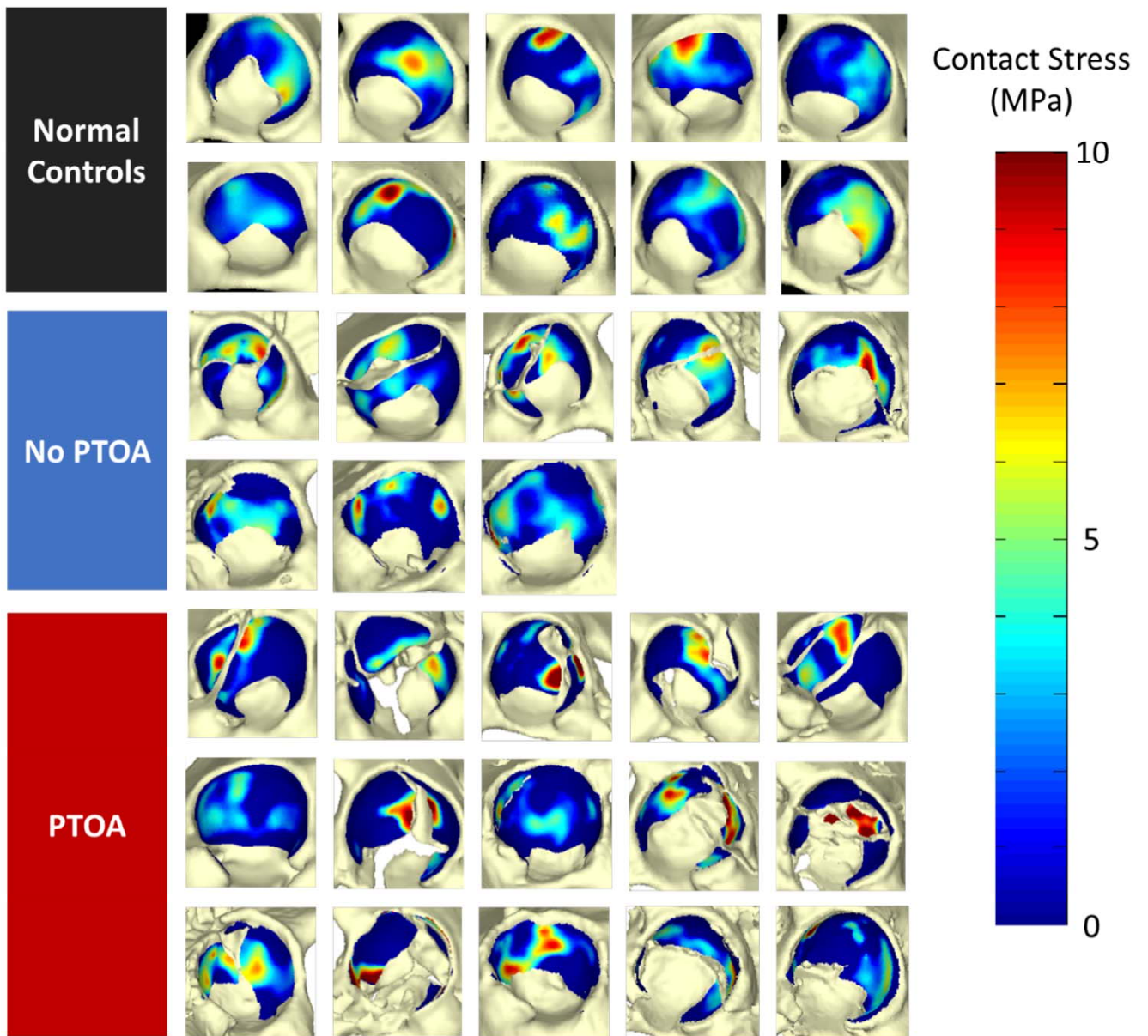
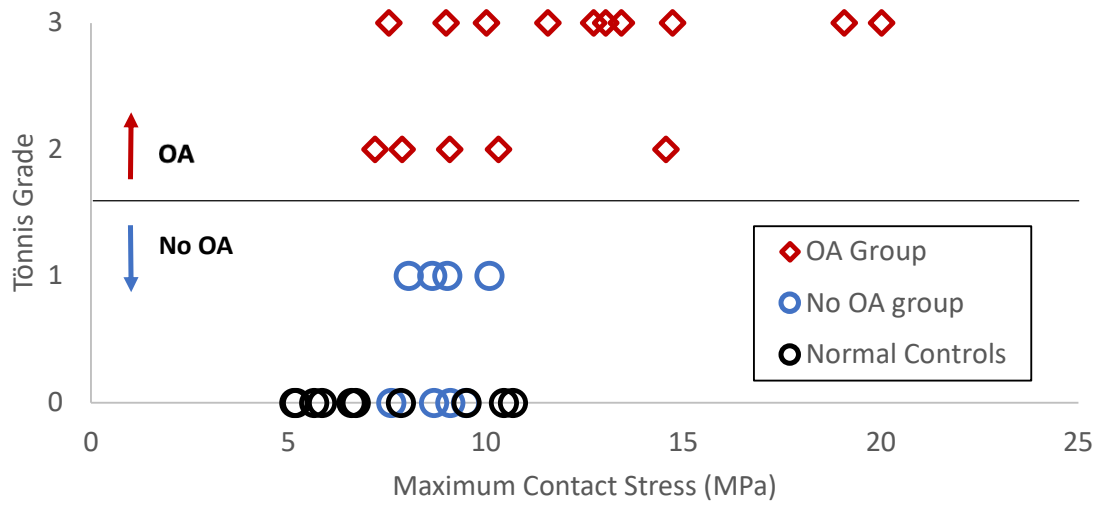


Figure 7. Elevated maximum contact stress is predictive of arthritic development when contact stresses exceed those of normal.



Objective Metrics of Tibial Pilon Fracture Severity Predict Secondary Amputation

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INTRODUCTION: Surgeons treating patients with high energy articular fractures of the tibial pilon face difficult treatment decisions. Primary treatment goals center on restoring limb function and avoiding post-traumatic osteoarthritis (PTOA). Reliably assessing the severity of the fracture is critical in decision making. Objective metrics of fracture severity (fracture energy, articular comminution) have been shown to reflect PTOA risk, but only in civilian patients with isolated joint fractures [1]. The goal of this study was to determine the utility of these fracture severity metrics in military patients, many of whom have additional fractured joints in their extremities and have limb salvage as a treatment goal.

METHODS: Twenty patients with tibial pilon fractures due to blast injuries were studied under IRB approval. These were the first analyzed from a larger series of patients being followed, with 15 of the 20 patients having follow-up data currently available. Fracture energy and articular comminution were computed from pre-op CT scan data [2]. The CT scans were segmented to identify and generate 3D surface models of all bone fragments. Bone surfaces were then classified into intact and de novo fracture surfaces. Bone densities were then used to scale interfragmentary surface areas to obtain the fracture energy [2]. Articular comminution was quantified as the articular fracture edge length – the length of the edge at the intersection between interfragmentary and subchondral bone surfaces. Outcomes were evaluated using KL radiographic grading of OA and by the rate of successful limb salvage.

RESULTS: Fracture energies ranged from 1.3 to 28.7 J (mean±SD = 11.9±8.0 J). Articular fracture edge lengths ranged from 18.5 to 256.1 mm (115.0±45.3 mm). For 15 patients with follow-up data, 1 extremity was amputated secondary to soft tissue reconstructive challenges and 4 due to pain and activity restriction. Of the limbs amputated late, two ankles had a KL grade of 3 and two a grade of 4. There was a statistically significant difference in the fracture energies of the amputation and retained limb groups (17.4 J vs 6.6 J, respectively; $p<0.01$) while articular fracture edge length differences trended towards significance (135.1 vs 105.3 mm; $p=0.06$). There were no significant differences in fracture severity metrics for different KL grades.

DISCUSSION: Fractures associated with blast injuries are generally considered severe and warrant thorough examination of treatment options. The present data suggest that objective CT-based metrics of fracture severity could provide reliable pre-op predictions of the risk of late amputation in military blast injuries that can help guide treatment decision-making.

REFERENCES: (1) Thomas TP et al. 2010. J Orthop Trauma 24(12):764-9. (2) Dibbern KN et al. 2017. J Orthop Research 35(3):618-24.

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Objective Assessment of Tibial Pilon Articular Fracture Severity Predictive of Secondary Amputation

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INTRODUCTION: Surgeons treating high energy articular fracture cases face difficult treatment decisions when attempting fracture reduction. Primary treatment goals center on restoring limb function and forestalling the onset of post-traumatic arthritis (PTOA). The tibial pilon is especially susceptible to PTOA development, making anatomical reduction of the tibiotalar joint crucial to long term function. Additionally, assessing fracture severity in these cases presents a critical component in treatment, with important implications for clinical and surgical decision making. Fracture energy and articular comminution have been utilized as measures to objectively assess fracture severity in the lower extremities and predict PTOA risk, but only in civilian patients with isolated joint fractures [1]. The goal of this study was to determine the utility of these same fracture severity measures in military patients, many of whom have additional fractured joints in their extremities, with limb salvage as a treatment goal.

METHODS: Twenty patients presenting with tibial pilon fractures resulting from blast injuries were studied under IRB approval. These were the first analyzed from a larger series of patients being followed, with 15 of the 20 patients having suitable follow-up data currently available. Fracture energy and articular comminution were computed from pre-operative CT scan data [2]. The CT scans were segmented to identify and generate 3D surface models of all bone fragments. Bone surfaces were then classified into intact and *de novo* fracture surfaces using a trained classification algorithm. Location-specific bone densities were then used to scale interfracture surface areas by density-dependent energy release rates to obtain the fracture energy. Articular comminution was incorporated by quantifying the articular fracture edge length, defined as the length of the edge at the intersection between interfracture and subchondral bone surfaces (Figure 1). Outcomes were evaluated using KL grading of radiographs and by the rate of successful limb salvage.

RESULTS: Fracture energies ranged from 1.3 to 28.7 J with a mean±SD of 11.9±8.0 J. Articular fracture edge length ranged from 18.5 to 256.1 mm with a mean±SD of 115.0±45.3 mm. Of the 15 patients with follow-up data available, 1 limb resulted in amputation secondary to soft tissue reconstructive challenges and 4 limbs were amputated due to the patients' pain and resultant activity restriction. Of the limbs that were amputated late, two had a KL grade of 3 and two had a KL grade of 4 for osteoarthritis grading of the ankle. There was a statistically significant difference in the fracture energies of the amputation and retained limb groups (17.4 J vs 6.6 J, respectively; p=0.0059) while articular fracture edge length differences trended towards significance (135.1 vs 105.3 mm; p=0.056). There were no significant differences in fracture energy or articular fracture edge length for different KL grades in this preliminary investigation.

DISCUSSION: Fractures associated with blast injuries are generally considered severe and warrant thorough examination of treatment options. The present data suggest that the amount of energy involved in a fracture, as well as the articular fracture edge length as a measure of articular comminution, may predict painful and activity limited post traumatic arthritis that contributes to late amputation in non-isolated military blast injuries. This preliminary investigation into pre-operative prediction of injury severity may offer insights into long term prognosis of such injuries.

SIGNIFICANCE: High energy injuries of the tibial pilon present complex treatment decisions. Objective measures of fractures severity may eventually provide pre-operative predictions of patient outcomes that can help guide initial operative management in cases where challenging decisions may exist.

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FIGURES:

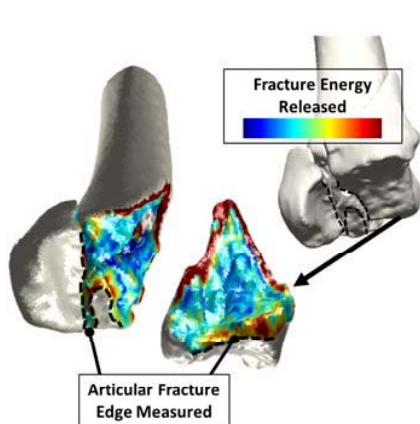


Figure 1. 3D model of a 10.1J fracture of the distal tibia with an exploded view of the fragments. The energy release rate variation across the interfracture surface is shown in color.

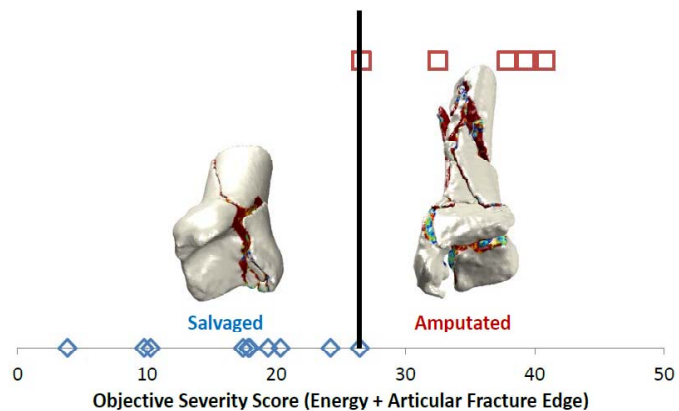


Figure 2. Objective Severity scores for 15 tibial pilon fractures. Successful salvages are shown in blue and amputations are shown in red.

Joint Contact Stress Correlates with Clinical Measures of Osteoarthritis in Surgically Reduced Acetabular Fractures

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Disclosures: H.D. Thomas: None. K.N. Dibbern: None. T.C. Holland: None. T.L. CarlLee: None. K. Rao: None. J.L. Marsh: None. M.C. Willey: None. J.E. Goetz: None. D.D. Anderson: None.

Introduction: Elevated contact stress following intra-articular fracture has been linked to subsequent development of post-traumatic osteoarthritis (PTOA). This relationship has been well established in the ankle,¹ and similarly, elevated contact stresses in the hip have been tied to osteoarthritic changes.² However, changes in hip contact stress due to articular fracture have not been well studied. Additionally, though elevated hip contact stresses due to residual incongruity have been documented in *in vitro* studies³, to our knowledge, they have never been studied in a series of clinical fracture cases. Therefore, the present study utilizes discrete element analysis (DEA) to investigate changes in contact stress that may occur in patients following surgical reduction of their intra-articular acetabular fractures and the relationship between elevated hip contact stress and clinical outcome in these patients.

Methods: Under IRB approval, post-operative CT scans from 10 surgically reduced acetabular fractures were obtained. 5 of these cases were considered to not have progressed to osteoarthritis (KL grade < 2, No OA group), and the remaining 5 cases were considered to have developed osteoarthritis (KL grade ≥ 2, OA group). Femoral and pelvic anatomy for each patient was segmented from their CT scan using a semi-automated program developed in MATLAB (Mathworks, Natick, MA). Each patient model was smoothed,⁴ aligned to the coordinate system defined by Bergmann *et al.*,⁵ and loaded with walking gait as determined from instrumented total hip gait data.⁵ Forces applied to each model were scaled based on the patient's body mass. DEA was used to compute contact stress during the stance phase of gait. For each patient, the maximum contact stress that developed at any time during the stance phase of gait was compared to their KL grade. The contact stress patterns for these two different groups of acetabular fracture patients were also compared over the full stance phase of gait to DEA-computed contact stresses in 5 trauma patients without hip pain or injury.

Results: The maximum contact stress for the OA group was 10.4 MPa, which was significantly ($p < 0.001$) higher than that for the No OA group (7.2 MPa) or for the patients with normal hips (8.9 MPa, Figure 1). While there was no significant difference in maximum contact stress between the No OA group and the patients with normal hips, the No OA group did have lower stress near heel-strike and higher stress near toe-off (Figure 1). There was a positive correlation between the maximum contact stress and KL grade ($R^2 = 0.546$, Figure 2).

Discussion: The acetabular fracture patients who developed osteoarthritis had significantly higher contact stress than the fracture patients who did not develop osteoarthritis and the patients with normal hips. This confirms that exposure to abnormally high contact stress in the hip leads to the development of osteoarthritis. The lack of a significant difference in contact stress between the fracture patients who did not develop osteoarthritis and the patients with normal hips indicates that the contact stress levels in both groups were less than that needed to initiate osteoarthritis development. However, the shift in maximum contact stress to later in the gait cycle for these fracture patients indicates that the surgical reductions have not returned the hip joints to a normal mechanical state.

Significance: DEA-calculated contact stress from post-operative CT scans was significantly higher in acetabular fracture patients who developed osteoarthritis and these higher stresses correlated with clinical measures of osteoarthritis. Therefore, DEA-calculated contact stress holds potential as an early predictor of patient specific clinical outcomes.

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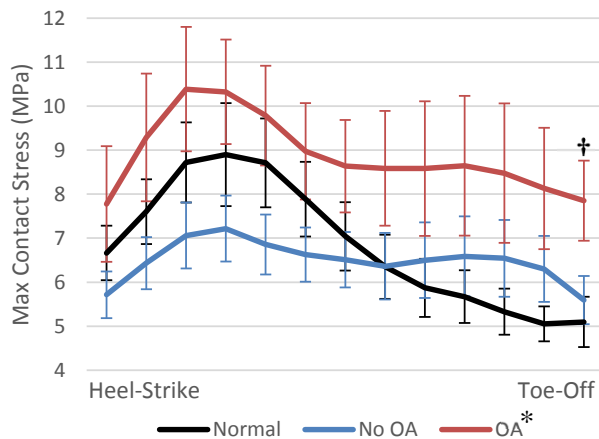


Figure 1: Over the entire stance phase of gait, the maximum contact stress in acetabular fracture patients who developed OA is significantly ($*p < 0.001$) higher than in fracture patients with no OA and normal hips. $N = 5$ per patient group. Fracture patients with no OA had higher contact stress near toe-off than patients with normal hips. $\dagger p < 0.05$, OA vs. normal.

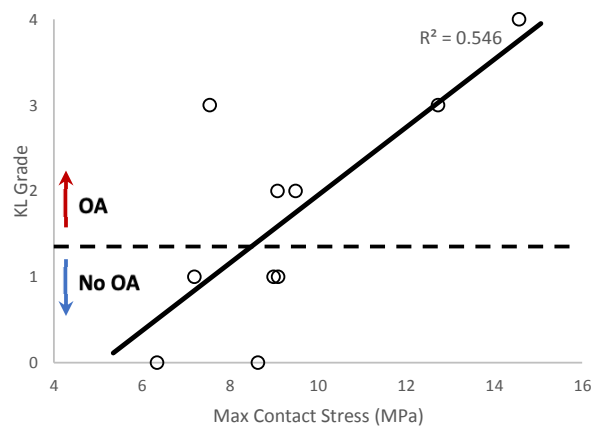


Figure 2: Maximum contact stress positively correlates with KL grade in surgically reduced acetabular fractures.



2018 International Foot and Ankle Biomechanics (i-FAB2018) Meeting

Dates: Sunday April 8th – Wednesday April 11th, 2018

Venue: Wyndham New Yorker Hotel, 481 8th Ave, NY, NY 10001

Welcome to the 2018 I-FAB meeting in New York City. We have an exciting scientific agenda in a truly unique venue planned. The meeting is problem based and multidisciplinary. The foot and ankle pathology or concern will be the focus of each session with presentations from the epidemiological, experimental, computational, and clinical perspectives. All related disciplines are encouraged to participate to enhance the breadth and depth of our conference.

This meeting is comprised of a pre-conference day that includes HSS laboratory tours and 4 tutorials. The conference includes 3 keynote addresses, the Alex Stacoff memorial award lecture, 4 special sessions, with 110 contributed abstracts that will be disseminated as podium and poster presentations. At the conclusion there will be a Best Podium, Best Poster, Best Student Podium, and Best Student Poster Award. We are fortunate to have 12 sponsors that have contributed substantially to the success of this meeting.

The social program includes a welcome reception to be held at the Wyndham New Yorker Hotel on the Mezzanine (Sunday 4/8/18 at 6:30PM – 8:30PM) and a banquet to be held on the Hornblower Hybrid Yacht (Tuesday 4/10/18 6:30PM – 10:30PM). Do not hesitate to ask our conference staff at the registration desk or your conference and program chairs for assistance.

Best wishes,

Howard J Hillstrom, PhD, Conference Chair HillstromH@HSS.edu
Jinsup Song, DPM, PhD, Program Chair JSong@Temple.edu

2018 I-FAB Program

Sunday April 8, 2018

- 9-11AM [HSS Lab Tours](#)
- 11:30AM Lunch in NYC
- 1-3PM [Tutorials A & B](#)
- 3:00PM Coffee Break
- 3:30PM [Tutorials C & D](#)
- 5:30PM Pre-conference Didactics Concluded
- 6-9PM [Welcome Reception](#)

Monday April 9, 2018

- 8AM Conference Welcome & Introduction
- 8:05AM [Keynote 1: Michael J. Coughlin, MD](#)
- 9AM [Session 1 - Total Ankle Replacement \(SS\)](#)
- 10:30AM Coffee Break with Vendors
- 11AM [Session 2 - Neuropathy & Motor Control](#)
- Noon Lunch in NYC
- 1:30PM [Session 3 - Pediatric Foot \(SS\)](#)
- 3:10PM [Session 4 - Vendor Technology Update](#)
- 3:20PM Coffee Break with Vendors
- 3:50PM [Session 5 - Military Biomechanics](#)
- 5:00PM [Session 6 - Tendon & Ligament Injuries](#)
- 6:00PM Adjourn

Tuesday April 10, 2018

- 8AM Daily Game Plan
- 8:05AM [Keynote 2: Marian T. Hannan, DSc, MPH](#)
- 9AM [Session 7 - Foot Type I](#)
- 10:10AM Coffee Break with Vendors
- 10:40AM [Session 8 - National Biomechanics Day & STEM](#)
- 11:00AM [Session 9 - Foot Type II](#)
- 12:10PM Lunch in NYC
- 1:30PM [Alex Staff Lecture: Don Anderson, PhD](#)
- 2:00PM [Session 10 - Ankle](#)
- 3:00PM [Session 11 - Hallux Rigidus and Hallux Valgus](#)
- 4:00PM ISB Footwear Biomechanics 2019
- 4:05PM [Session 12a - Poster Teasers](#)
- 4:15PM [Session 12b - Posters and Coffee](#)
- 5:30PM Adjourn
- 7-10PM [Congress Banquet](#)

Wednesday April 11, 2018

- 8AM Daily Game Plan
- 8:05AM [Keynote 3: Marcus G. Pandy, PhD](#)
- 9AM [Session 13 - Healthy Locomotion](#)
- 10:00AM Coffee Break with Vendors
- 10:30AM [Session 14 - Good Vibrations \(SS\)](#)
- 12:00PM Lunch in NYC
- 1:30PM [Session 15 - Sports Injuries](#)
- 3:20PM Coffee Break
- 3:40PM [Session 16 - Minimalist Shoes \(SS\)](#)
- 5:10PM Awards and Congress Wrap-up
- 5:30PM Adjourn

Note: SS = Special Session

Keynotes

Keynote 1: Monday 8:05AM - 9AM **Michael J Coughlin, MD**

“Total Ankle Design: What is Being Done in America and Around the World”

Moderator: Scott Ellis, MD (HSS)

Keynote 2: Tuesday 8:05AM - 9AM **Marian T. Hannan, DSc, MPH**

"Out of the Lab and Into the Streets: Population-Based Epidemiology Of Foot Pathologies"

Moderator: Howard Hillstrom, PhD (HSS)

Stacoff Memorial Lecture: Tuesday 2PM - 2:30PM **Donald D. Anderson, PhD**

"Enabling Post-Traumatic Osteoarthritis Risk Prediction from Pathomechanics"

Moderator: William Ledoux, PhD (University of Washington, Seattle VA)

Keynote 3: Wednesday 8:05 - 9AM **Marcus G. Pandy, PhD**

"Muscle and Joint Function in Human Gait"

Moderator: Alberto Leardini, PhD (Istituto Ortopedico Rizzoli)

Donald D. Anderson, PhD

Don Anderson is Professor and Vice-Chair of Research in the Department of Orthopedics & Rehabilitation at the University of Iowa, where he directs the Orthopaedic Biomechanics Laboratory. Dr. Anderson holds a BSE in Biomedical Engineering, as well as an MS and PhD in Mechanical Engineering, all from the University of Iowa. He has nearly 30 years of post-doctoral experience with image analysis, computer modeling, and computational stress analysis in musculoskeletal applications. Dr. Anderson's primary research focus is articular joint biomechanics, and his most recent work involves the scaling up of methods for patient-specific articular joint modeling in the ankle.



“Enabling Post-Traumatic Osteoarthritis Risk Prediction from Pathomechanics”

The long-term goal of our research is to forestall post-traumatic osteoarthritis (PTOA), the disabling condition that often develops after joint injuries like an intra-articular fracture (IAF) of the tibial plafond. PTOA leads to permanent disability in nearly 30% of individuals having sustained an IAF, with those of the foot and ankle being the most disabling. The impairment associated with ankle OA is comparable to that caused by end-stage kidney disease or congestive heart failure. The vast majority of ankle OA is post-traumatic, with tibial plafond IAFs often leading to disabling PTOA within two to five years. As a result, patients with ankle injuries provide an ideal population in which to study this degenerative pathway so that we can optimize treatment. We have developed patient-specific precision medicine approaches to predict PTOA risk in the ankle using CT-based measures of pathomechanical factors associated with IAFs (fracture severity and elevated contact stress post-treatment) of the tibial plafond. A primary objective of the group's present work is to enable the use of these innovative methods for assessing IAFs to better inform patient care and to guide future clinical trials of new therapies directed at mitigating or arresting the environment that triggers progressive joint degeneration.

ELEVATED CONTACT STRESS AFTER ACETABULAR FRACTURE CORRELATES WITH DEVELOPMENT OF RADIOGRAPHIC OA

Holly D. Thomas, Kevin N. Dibbern, Tai C. Holland, J. Lawrence Marsh, Michael C. Willey, Jessica E. Goetz, Donald D. Anderson
 University of Iowa, Iowa City, IA — don-anderson@uiowa.edu

Purpose: Elevated contact stress following intra-articular fracture has been linked to subsequent development of post-traumatic osteoarthritis (PTOA). This relationship has been well established in the ankle, and elevated contact stresses in the hip have been tied to osteoarthritic changes. However, changes in hip contact stress due to articular fracture have not been well studied. Additionally, though elevated hip contact stresses due to residual incongruity have been documented in *in vitro* studies, to our knowledge, they have never been studied in a series of clinical fracture cases. Therefore, the present study utilizes discrete element analysis (DEA) to investigate changes in contact stress that may occur in patients following surgical reduction of their intra-articular acetabular fractures and the relationship between elevated hip contact stress and radiographic OA outcome in these patients.

Methods: Under IRB approval, post-operative CT scans from 10 patients with surgically reduced acetabular fractures were obtained. Five of the cases were considered to not have progressed to OA (KL grade < 2, No OA group), and the remaining five were considered to have developed OA (KL ≥ 2, OA group). Femoral and pelvic anatomy for each patient was segmented from CT using a semi-automated program developed in MATLAB (Mathworks, Natick, MA). Each patient model was smoothed, aligned to an appropriate coordinate system, and moved through a series of loadings drawn from gait data collected using an instrumented total hip. Forces applied to each model were scaled based on the patient's body weight. DEA was used to compute contact stress during the stance phase of gait. For each patient, the maximum contact stress that developed at any time during the stance phase of gait was compared to their KL grade. The contact stress patterns for these two different groups of acetabular fracture patients were also compared over the full stance phase of gait to DEA-computed contact stresses in 5 trauma patients without hip pain or injury.

Results: The maximum contact stress for the OA group was 10.4 MPa, which was significantly ($p < 0.001$) higher than that for the No OA group (7.2 MPa) or for the patients with normal hips (8.9 MPa, Figure 1). While there was no significant difference in maximum contact stress between the No OA group and the patients with normal hips, the No OA group did have lower contact stress near heel-strike and higher contact stress near toe-off (Figure 1). There was a positive correlation between the maximum contact stress and KL grade ($R^2 = 0.546$, Figure 2).

Conclusions: The acetabular fracture patients who developed OA had significantly higher contact stress than the fracture patients who did not and the patients with normal hips. This suggests that exposure to abnormally high contact stress in the hip leads to the development of OA. The lack of a significant difference in contact stress between the fracture patients who did not develop OA and the patients with normal hips indicates that the contact stress levels in both groups were less than that needed to initiate OA development. However, the shift in maximum contact stress to later in the gait cycle for these fracture patients indicates that the surgical reductions have not returned the hip joints to a fully normal mechanical state. DEA-calculated contact stress holds potential as an early predictor of patient specific radiographic outcomes.

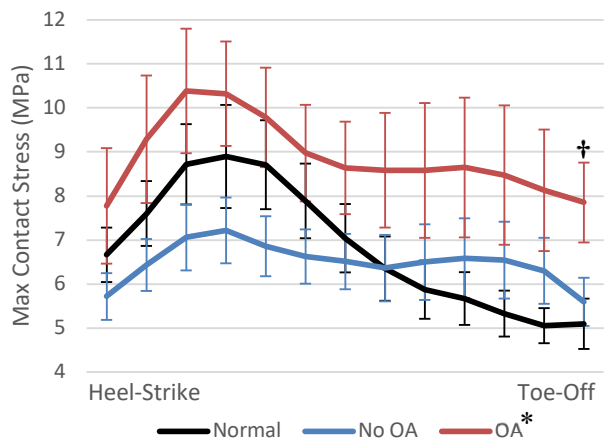


Figure 1: Over the entire stance phase of gait, the maximum contact stress in acetabular fracture patients who developed OA is significantly ($*p < 0.001$) higher than in fracture patients with no OA and normal hips. $N = 5$ per patient group. Fracture patients with no OA had higher contact stress near toe-off than patients with normal hips. $†p < 0.05$, OA vs. normal.

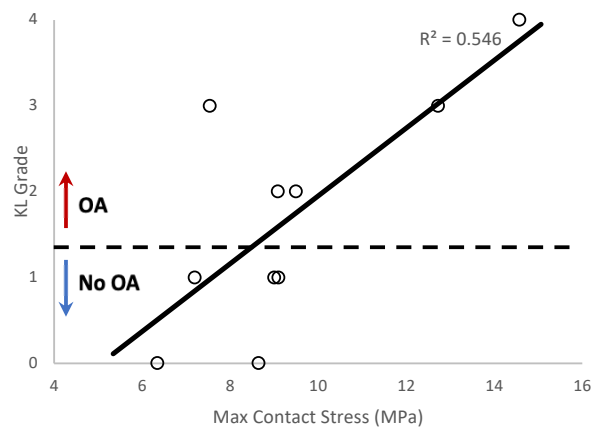
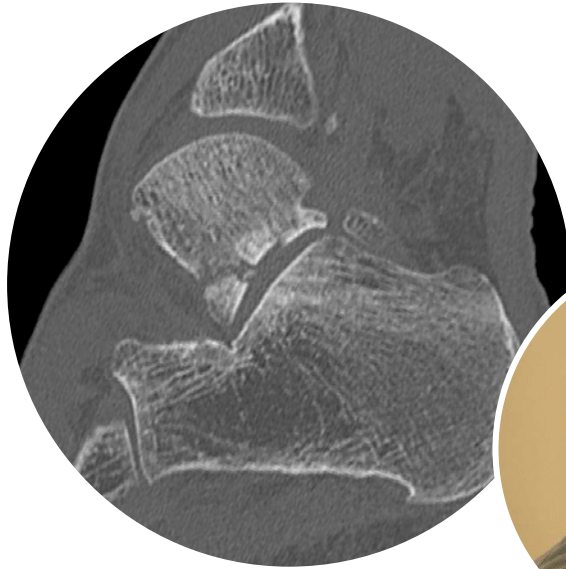


Figure 2: Maximum contact stress positively correlates with KL grade in surgically reduced acetabular fractures.



Enabling Post-Traumatic Osteoarthritis Risk Prediction from Pathomechanics

Presented by the Engineering Solutions for Health:
Biomedical Engineering Research Strategy

June 6th, 2018

11:30 a.m. – 12:30 p.m.

Kinesiology B, Room 427

University of Calgary

Free and Open to the Public

Dr. Don Anderson

University of Iowa

Professor, Vice-Chair Research

Department of Orthopaedics

and Rehabilitation

Post traumatic osteoarthritis (PTOA) leads to permanent disability in nearly 30% of individuals having sustained an intra-articular fracture (IAF), with those of the foot and ankle being the most disabling. Dr. Anderson's group has developed patient-specific precision medicine approaches to predict PTOA risk in the ankle using CT-based measures of pathomechanical factors associated with IAFs (fracture severity and elevated contact stress post-treatment) of the tibial plafond. Dr. Anderson's group aims to enable the use of innovative methods for assessing IAFs to better inform patient care and to guide future clinical trials of new therapies directed at mitigating or arresting the environment that triggers progressive joint degeneration.

Novel severity measures link fractures from cadaveric experiments to those in battlefield blast cases

Kevin N. Dibbern¹, Brandon J. Perry², Edward M. Spratley², Robert S. Salzar², Jessica C. Rivera³, [Donald D. Anderson](#)¹

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Abstract

Introduction

Explosive blasts are one of the most common battlefield injury mechanisms leading to lower extremity fractures. Reproducing such injuries in a laboratory setting is difficult given the extreme loading rates seen in blast relative to prior experimental tests [1]. This study sought to compare the fracture characteristics of a series of battlefield blast cases with those of three high-rate laboratory models. Accurately and rigorously characterizing the severity, location, and type of injuries in both battlefield cases and laboratory models is paramount; therefore, novel objective, physically-based measures that can be quantified on continuous scales are necessary. For this purpose, fracture mechanics methods were used to provide objective metrics of severity.

Methods

Pre-operative CT scans from 42 battlefield blast cases were analyzed for comparison with CT scans obtained from laboratory testing of 36 cadaveric lower extremity specimens. Three testing conditions designed to replicate battlefield blast fractures were used in the laboratory with low, intermediate, and high loading rates. Fracture energy measures were calculated from post-fracture CT scans using validated methods [2]. A new measure, the mean energy-release distance (MERD), was also calculated to characterize the location and distribution of fractures. The MERD was defined as the proximal distance from the distalmost aspect of the calcaneus at which 50% of the total fracture energy had been dissipated.

Results

The battlefield blast cases had fracture energies (mean±SD) of 15.2±8.1J and MERDs of 63.4±42.4mm (Figure 1). The laboratory low, intermediate, and high impact conditions had fracture energies of 12.7±7.8J, 19.5±8.8J, and 23.5±7.7J, along with MERDs of 33.6±31.2mm, 53.6±31.7mm, and 38.9±25.9mm, respectively. There were no significant differences in the fracture energies between battlefield blast cases and the low (P=0.33) or intermediate (P=0.13) impact groups. The high impact group had significantly more energy released (P=0.0026). Significant difference was seen between the MERDs for the battlefield blast cases and the intermediate impact group (P=0.019), while non-significant differences were seen with the intermediate (P=0.48) and high (P=0.063) impact groups.

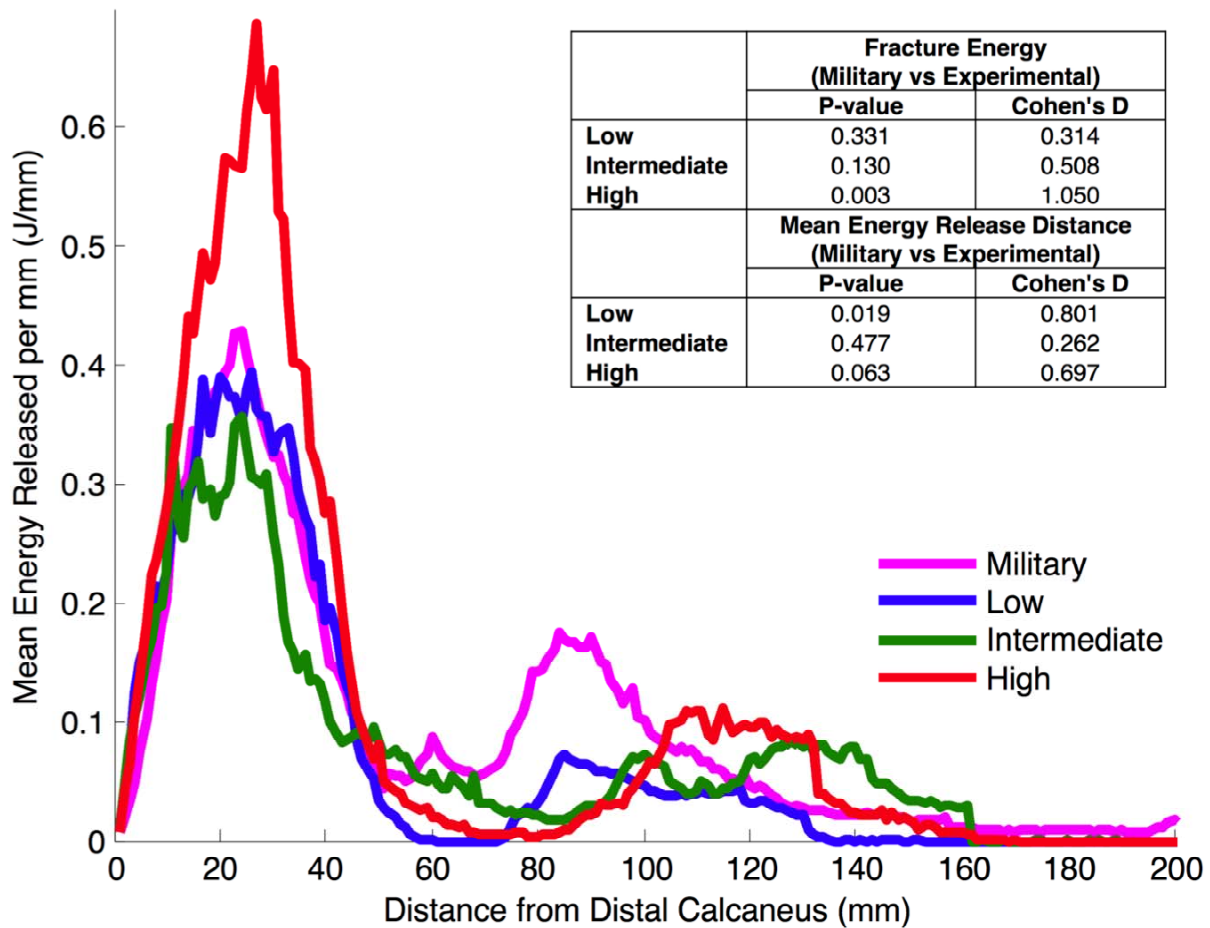


Figure 1. Plots of the mean fracture energy released across each group as it varies along the distance from the distalmost aspect of the calcaneus over the fractured segment of the lower extremity.

Discussion

These results indicate that the intermediate impact protocol produced fractures most closely representative of battlefield blast injuries in both overall fracture energy and in its distribution. This methodology can be used to inform and improve injury models by bridging the gap between experimental and clinical results.

References

[1] Henderson et al. Proc IRCOBI Conference, 2013. [2] Dibbern et. al. J Orthop Res 35:618-24, 2017.

Acknowledgments

Research reported in this abstract was supported by the Assistant Secretary of Defense for Health Affairs through the Peer Reviewed Medical Research Program under Award No. W81XWH-15-2-0087. Cadaveric specimens were procured and tested in accordance with University of Virginia IRB-HSU# CAB 2015-02.

Elevated contact stress after acetabular fracture correlates with the development of radiographic OA

Holly D. Thomas-Aitken, Kevin N. Dibbern, Tai C. Holland, J. Lawrence Marsh, Michael C. Willey, Jessica E. Goetz, Donald D. Anderson
University of Iowa, Iowa City, USA.

Abstract

Introduction

Elevated contact stress following intra-articular fracture correlates with the development of post-traumatic osteoarthritis (PTOA) in the ankle [1], but the relationship has yet to be studied in the hip. The present study utilizes validated patient-specific discrete element analysis (DEA) techniques [2] to investigate contact stress in patients following surgical reduction of their intra-articular acetabular fractures to see if elevated hip contact stress correlates with radiographic OA outcome.

Methods

Under IRB approval, post-operative CT scans from 10 patients with surgically reduced acetabular fractures were obtained. Five of the cases were considered to not have progressed to OA (KL grade < 2, No OA group), and the remaining five were considered to have developed OA (KL \geq 2, OA group). The patient-specific bony anatomy of the hip was segmented from CT using a semi-automated program developed in MATLAB. Each patient model was smoothed, aligned to an appropriate coordinate system, and subjected to a series of loadings (scaled by body weight) drawn from gait data collected using an instrumented total hip [3]. DEA was used to compute contact stress during the stance phase of gait. For each patient, the maximum contact stress that developed during the stance phase of gait was compared to their KL grade. The contact stress patterns for these two different groups of acetabular fracture patients were also compared over the full stance phase of gait to DEA-computed contact stresses in 5 trauma patients without hip pain or injury.

Results

The maximum contact stress for the OA group was 10.4 MPa, which was significantly ($p < 0.001$) higher than that for the No OA group (7.2 MPa) and for the patients with normal hips (8.9 MPa, Figure 1). While there was no significant difference in maximum contact stress between the No OA group and the patients with normal hips, the No OA group did have lower contact stress near heel-strike and higher contact stress near toe-off. Maximum contact stress was positively correlated with the KL grade ($R^2 = 0.55$).

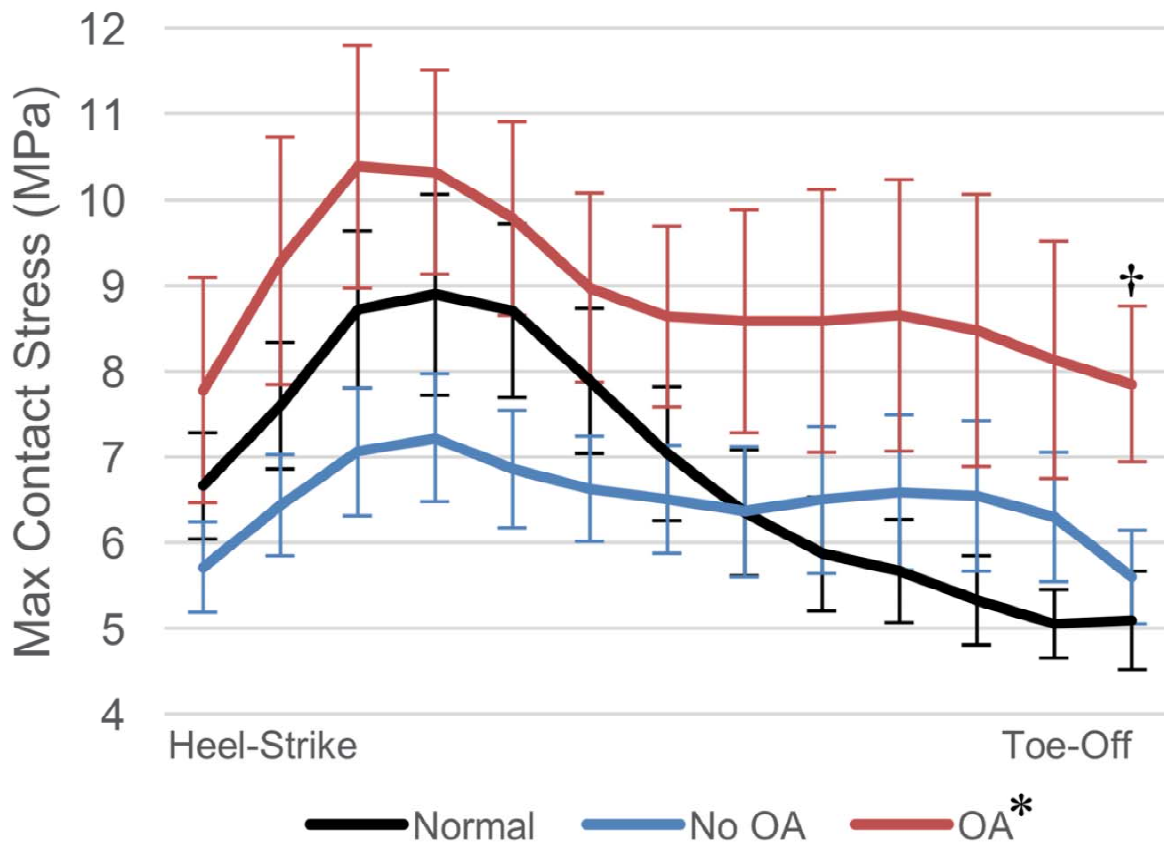


Figure 1: Over the entire stance phase of gait, the maximum contact stress in acetabular fracture patients who developed OA is significantly ($*p < 0.001$) higher than in fracture patients with no OA and normal hips. $N = 5$ per patient group. Fracture patients with no OA had higher contact stress near toe-off than patients with normal hips. † $p < 0.05$, OA vs. normal.

Conclusions

The results of this study suggest that exposure to abnormally high contact stress in the hip following acetabular fracture leads to PTOA. However, the shift in maximum contact stress to later in the gait cycle for these fracture patients indicates that the surgical reductions have not returned the hip joints to a fully normal mechanical state. DEA-calculated contact stress holds potential as an early predictor of patient specific radiographic outcomes.

Acknowledgments

The research reported in this abstract was supported by the National Institutes of Health under award number P50 AR055533.

References: [1] Anderson DD, et al. J Orthop Res 29(1), 2011. [2] Townsend KC, et al. J Biomech, 2017. [3] Bergmann G, et al. J Biomech 34, 2001.

CONTACT STRESS OVER-EXPOSURE CORRELATES WITH OA DEVELOPMENT IN ACETABULAR FRACTURES

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INTRODUCTION

Posttraumatic osteoarthritis (PTOA) is a common debilitating sequela of intra-articular fracture (IAF) [1]. Surgical reduction of IAFs aims to restore congruity of the disrupted joint surface to decrease articular contact stress and mitigate PTOA risk [2]. Elevated contact stress in mal-reduced IAFs of the ankle reliably predicts PTOA risk [3]. The effect of acetabular fracture on chronic hip contact stress and PTOA risk, however, is less well established. With up to a quarter of acetabular IAFs leading to PTOA, an investigation into the pathomechanical development of this condition is warranted.

Computational modeling of articular contact derived from CT images has been well validated for contact stress assessment. Discrete element analysis (DEA) is a specific modeling technique well suited for determining relationships between contact stress exposures and clinical outcomes, such as PTOA, in larger patient populations [6]. Mapping of the cumulative contact stress over-exposure on the articular surface across a complete gait cycle provides a means to identify those joints most prone to eventual development of PTOA.

METHODS

Eleven patients with operatively managed acetabular fractures were enrolled in this IRB-approved study. Patients were selected for having post-operative CT imaging and minimum two-year radiographic follow-up available. Femoral and pelvic anatomy for each patient was segmented from post-operative CT scans to produce DEA models using the validated method of Townsend et. al., 2018. The models were then aligned to the coordinate system defined by Bergmann et al. The walking gait data obtained in that study of instrumented total hips was discretized into 13 evenly spaced time increments. Patient

specific forces were applied to each model based on body mass at the time of injury. DEA was used to compute deleterious contact stress exposure above a damage threshold ($P_d \geq 5$ MPa – defined as over-exposure) at each step in the gait cycle. For each patient, only the deleterious contact stress over-exposure was considered in our evaluation. These deleterious contact stresses were then computed at each of the 13 steps of the gait cycle and multiplied by the time spent in each of the steps to obtain a stress-time over-exposure metric. Summed over the gait cycle, the cumulative contact stress over-exposure experienced by the articular surface was compared to KL grades at 2 years post-operatively.

RESULTS AND DISCUSSION

Maximum values of contact stress over-exposure per gait cycle ranged from 0.23 - 2.91 MPa*s in the 11 acetabular cases analyzed in this study (Fig. 1). By design, KL grades were evenly distributed with 2 cases per grade except for grade 1 with 3 cases. Maximum per gait cycle contact stress over-exposure stress had a moderate positive correlation with KL grade ($R^2 = 0.426$). Qualitative assessment of the DEA derived post-operative models of this subset (cases 07, 08, and 10) reveals acetabular fractures with readily apparent joint incongruities flanked by areas of high contact stress over-exposure (Fig. 2). Cases with minimal or no radiographic evidence of osteoarthritis tended to exhibit better articular surface congruity. This corresponded with lower maximum contact stress over-exposure.

To our knowledge, this is the first study investigating the relationship between cumulative contact stress over-exposure and PTOA in acetabular fractures. The maximum per-gait cycle contact stress over-exposure cycle exhibited a

threshold above which all acetabular fractures progressed to PTOA.

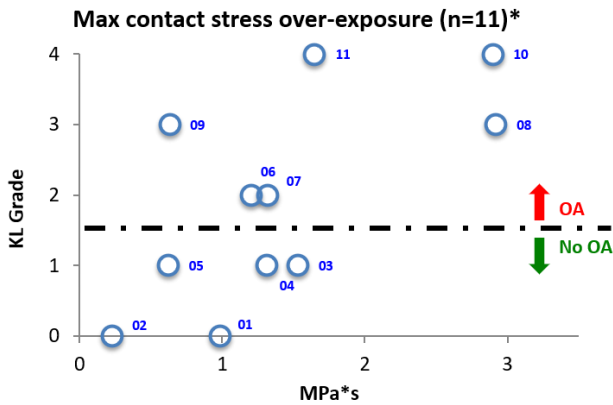


Figure 1: Maximum per gait cycle contact stress over-exposure.

CONCLUSION

The rate of PTOA development after surgical reduction and repair of acetabular fractures has remained stagnant over the years. Major efforts have focused on improving surgical technique to prevent PTOA, despite limited success and poor understanding of the pathogenesis of PTOA. Investigating how disruptions of articular surfaces can cause PTOA will likely provide insight on how to properly reconstruct them. The methods developed in this work allow precise and objective determination of the quality of acetabular fracture

reduction. DEA techniques can quantify the mechanical impact of imperfect reduction via calculation of contact stress elevations throughout articular surfaces.

SIGNIFICANCE

The application of these techniques to acetabular fractures highlights the clinical value of this methodology in the hip joint. By identifying hips likely to degenerate due to a high level of residual incongruity, DEA-contact stress analysis may provide early prediction of joint failure and subsequent consideration of conversion to total hip arthroplasty.

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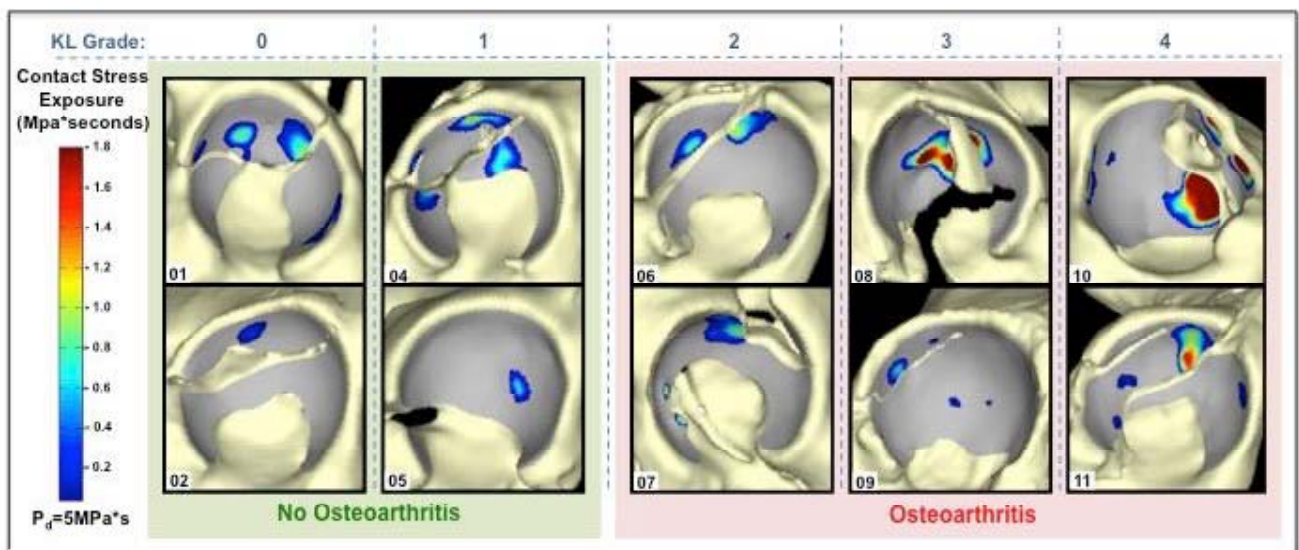


Figure 2: The distribution and magnitude of deleterious exposure (>5MPa*s) in acetabular fractures. Patient cases arranged by increasing KL grade and grouped by radiographic outcome.