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TITLE: Pathomechanics of Post-Traumatic OA Development in the Military Following Articular Fracture

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| 13. SUPPLEMENTARY NOTES                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |              |                          |                            |                                               |                                           |
| 14. ABSTRACT<br>The objective of the proposed research is to develop new models for predicting the risk of post-traumatic osteoarthritis (PTOA) following intra-articular fracture (IAF). Aim 1, pursued this year, involves evaluating pre- and post-treatment CT data from patients with combat-related IAFs to measure fracture severity and post-reduction contact stress exposure. We first established a CRADA between the University of Iowa and the U.S. Army Institute of Surgical Research (USAISR). Then IRB approval for access to the patient data from the military medical record was obtained. Our partner at USAISR is screening the DoDTR to identify and enroll subjects. The imaging data for 42 subjects were forwarded to Iowa for analysis, with another 16 subjects identified and their imaging studies requested.<br><br>As part of an unrelated grant from the NIH, civilian patient data were equivalently analyzed this year, which required refining existing methodologies. Analysis was completed for 31 tibial plafond, 61 tibial plateau, and 17 intra-articular calcaneal fracture cases. We published two papers based on results from those civilian data. Success in analyzing these cases supports our belief that we will be successful in analyzing military CT scan data as they become available. |              |                          |                            |                                               |                                           |
| 15. SUBJECT TERMS<br>post-traumatic osteoarthritis, CT-based analysis, intra-articular fractures                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |              |                          |                            |                                               |                                           |
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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:

|                                                                                                                                                                                |        |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------|
| <b>Specific Aim 1:</b> Evaluate pre- and post-treatment CT data from patients with combat-related IAFs to measure fracture severity and post-reduction contact stress exposure |        |
| <b>Major Task 1:</b> 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    |
| <b>Major Task 2:</b> 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   |
| <b>Major Task 3:</b> 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     |
| <b>Major Task 4:</b> 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  |

|                                                                                                                 |        |
|-----------------------------------------------------------------------------------------------------------------|--------|
| <b>Specific Aim 2:</b> Measure the occurrence of PTOA up to ten years following fracture reduction surgery      |        |
| <b>Major Task 5:</b> 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  |

|                                                                                                                                      |        |
|--------------------------------------------------------------------------------------------------------------------------------------|--------|
| <b>Specific Aim 3:</b> Quantify the extent to which fracture severity and post-reduction contact stress predict PTOA                 |        |
| <b>Major Task 6:</b> 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)** is now completed.

- Final regulatory approval received (HRPO Log Number A-18855) --- 23-10-2015

**Major Task 2 (adapt CT analysis methods)** is nearly completed. [Please see text below for details related to activities outlined in this introductory paragraph.] We have developed new more universally-applicable analysis methods for assessing fracture severity in any fracture for which pre-op CT scans are available. We are presenting an abstract at the Annual Meeting of the Orthopaedic Research Society detailing the methods in March 2017. We have published in the Journal of Orthopaedic Trauma a report based on results obtained using these new methods in the last year working from civilian subject CT studies. Developments in that civilian subject-based work directly support our ongoing work with military subjects. A second manuscript based on those results has been published in a special issue of the Journal of Orthopaedic Research dedicated to Post-traumatic Osteoarthritis. Finally, we will be presenting an abstract at the OARSI World Congress in April 2017 detailing our latest civilian data linking fracture severity to PTOA development.

- Modifications required in analysis code outlined and begun --- 15-03-2015
- Modifications to analysis code completed --- 01-06-2016
- J Orthop Trauma manuscript accepted for publication 18-05-2016.
- J Orthop Research manuscript accepted for publication 30-06-2016.
- Abstract to be presented at ORS Annual Meeting 19-03-2017.
- Abstract to be presented at OARSI World Congress 27-04-2017.

## **Detailed report of progress on Major Task 2**

### *New fracture severity assessment methods based on pre-op CT*

In our earlier work, we developed objective techniques to measure fracture severity from CT scan data. Fracture severity was assessed primarily based on the energy released in fracture, which is directly related to the amount of inter-fragmentary bone surface liberated (Figure 1).

These techniques, as originally developed, were dependent upon a CT scan of the intact contralateral bone, which is rarely available for the military fractures now being studied. Furthermore, fracture energy had previously been analyzed only in a single joint (the ankle), and we now need to evaluate fractures in other joints.

To expand the clinical utility of fracture energy as an objective metric of severity, we have developed new methods to implement fracture energy as a universal tool in any fracture with pre-operatively available CT-scans (Figure 2). CT images are first segmented, identifying all bone fragments, to generate a 3D model of the fracture. Surfaces are then smoothed to remove voxelation effects 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 is quantified by measuring the fracture edge length along the articular surface from the fractured surface boundaries, a parameter chosen based on prior in vitro work establishing a high degree of chondrocyte death along fracture edges.

We validated this new methodology by comparing the fracture energies obtained for a series of 20 tibial pilon fractures using the new methods to values previously obtained using our original methods. A Bland-Altman plot comparing the results is shown in Figure 3. There was strong agreement between the previous fracture energy evaluation method and the expanded methodology, with all but one case lying within the 95% confidence interval. On average, there was a bias that the prior methodology measured around 1.5Joules (J) higher than the present method. Based upon these cases, the data suggest that 95% of measurements with the new methodology will be within 3-5J of those made using prior methods.

Follow-up work explored the hypothesis that fracture severity metrics are higher in tibial plafond than in plateau fractures, which could explain why plafond fractures are more susceptible to PTOA than plateau fractures. This multi-center clinical study involved a larger and more diverse group of patients, including seventy-five tibial plateau fractures and fifty-two tibial plafond fractures

**Figure 1.** Custom software is used to measure the area of inter-fragmentary bone surfaces. The fracture-liberated surface area and bone densities on that surface are used to calculate fracture energy. The length of the edge between the subchondral and inter-fragmentary bone surfaces (the articular fracture edge length) is used to quantify articular surface involvement.

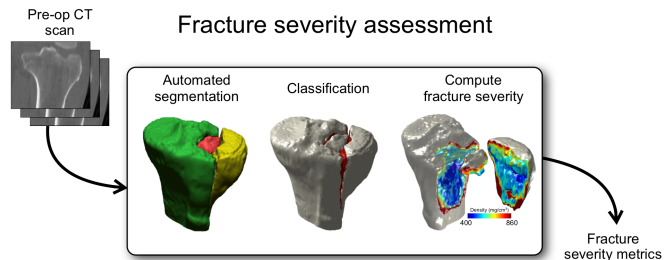


**Figure 2.** Schematic of new assessment methods

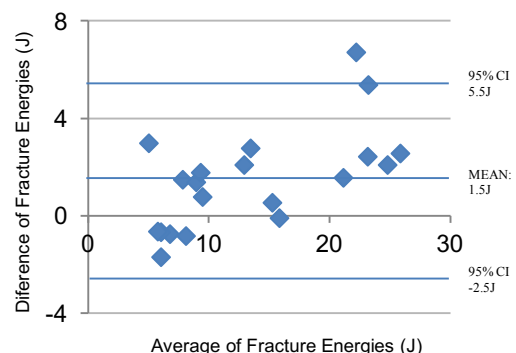


**Figure 3.** Bland-Altman plot comparing fracture energies obtained from the old and new methods.

spanning the spectrum of severity. The range of fracture energies measured for tibial plateau fractures was 3.2-33.2J. The range of fracture energies for pilon fractures was 3.6-32.2J. The fracture energies (mean $\pm$  standard deviation) of the plateau fractures were 13.3 $\pm$  6.8J, and they were 14.9 $\pm$  7.1J for the pilon fractures. The range of articular fracture edge lengths measured for tibial plateau fractures was 68.0-493.0mm. The range of articular fracture edge lengths for pilon fractures was 56.1-288.6mm. The articular fracture edge lengths (mean  $\pm$  standard deviation) of the plateau fractures were 231.4  $\pm$  94.7mm, and they were 138.1  $\pm$  54.9mm for the pilon fractures. Summarizing, we found no differences in fracture energies between the two fracture types, but plateau fractures had greater involvement of the articular surface ( $p<0.001$ ). Similar fracture energies and greater articular involvement in the tibial plateau suggest that it may be more tolerant of impact injury compared to the tibial plafond.

We have recently also measured fracture severity in patients with IAFs of the distal radius, calcaneus, and acetabulum (Figures 3, 4). Fracture energies varied between joints with higher/lower levels for some and wider/narrower ranges for some. These unique features may explain part of the differences in PTOA propensity among these different joints.

In subsequent work, we tested the hypothesis that the severity of an IAF, independent of the joint it involves, can be used as a predictor of PTOA risk. Sixty-one civilian patients presenting with IAFs of their acetabulum ( $n=17$ ), calcaneus ( $n=13$ ), or distal tibia ( $n=31$ ) were consented for retrospective study. Patients were selected from a larger series based on availability of pre-op CT scans and a minimum of 20-month radiographic follow-up. Objective assessment of fracture severity involved measuring the fracture energy and the degree of articular involvement from pre-op CT scans. The length of the fracture edge at the joint surface was normalized to account for variation in the amount of articular surface between different joints. Outcomes were evaluated using Kellgren-Lawrence (KL) grading of radiographs for indicators of OA taken at least 20 months' post-injury, and PTOA presence was defined as a KL grade  $\geq 2$ . The relationship between IAF severity (defined as fracture energy or articular fracture length) and PTOA development was modeled using logistic regression.

Fracture energies ranged from 3.6 to 32.8J with a mean  $\pm$  SD of 16.4  $\pm$  6.8J, and the articular fracture

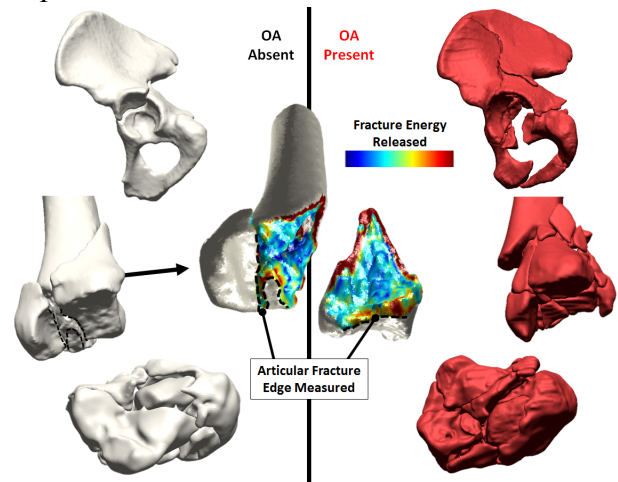


**Figure 3.** Objective severity assessment for a variety of intra-articular fractures.

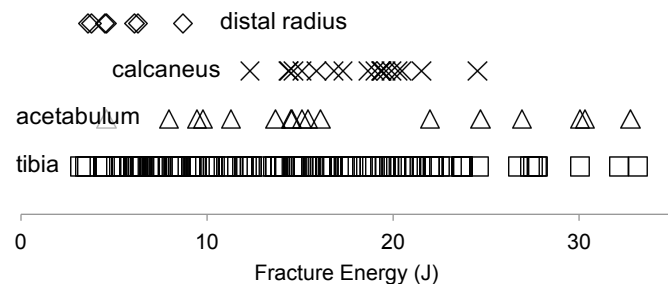


**Figure 4.** Fracture energies in IAFs of the distal radius, calcaneus, acetabulum, and tibia (plateau and plafond).

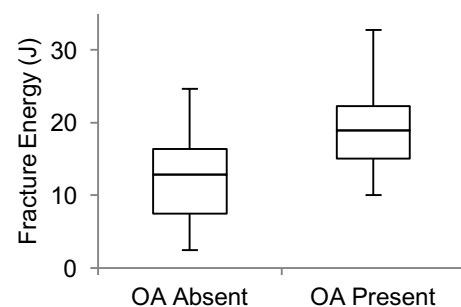


**Figure 5.** Fracture energy and PTOA risk.

edge lengths ranged from 35.8 to 364.8mm with a mean  $\pm$  SD of  $146.0 \pm 78.1$ mm. Thirty-five fractured joints (57% of those studied) had developed PTOA ( $KL \geq 2$ ) at their longest follow-up. Both fracture energy ( $p < 0.001$ ; Figure 5), and scaled articular fracture edge length ( $p < 0.01$ ) were found to be strongly predictive of PTOA risk, findings consistent with our prior work that only included the ankle joint. These results give us even greater confidence regarding the value of these methods for objectively quantifying fracture severity to provide a predictor of PTOA risk following IAF.

#### *New contact stress assessment methods based on post-op joint models*

We had originally developed techniques to index chronic contact stress elevations by patient-specific finite element analysis (FEA), using models derived from post-reduction CT scans. The prohibitive costs and inherent challenges of performing 3D contact FEA on a subject- or patient-specific basis makes FEA of questionable utility for study of the role of aberrant levels of articular contact stress in PTOA risk, at least for larger patient series needed to show statistically robust causality. We adopted an alternative numerical approach to modeling articular contact called discrete element analysis (DEA). DEA involves treating bones as rigid bodies, and the cartilage as an array of compressive-only springs distributed over the articulating bony surfaces. We first established the equivalence of DEA and FEA results for the post-op contact stress exposures in 11 patients with tibial plafond fractures as predictors of PTOA risk. We then extended our DEA methods for application in the subtalar joint (IAF of the calcaneus) and in the hip (IAF of the acetabulum – Figure 7). Importantly, we have also shown that this approach can be highly automated (Figure 8), an advance predicated on the availability of a post-op CT scan. However, changing practice patterns have recently led to much less routine acquisition of these CT scans.

To move away from a reliance upon post-op CTs, we have developed methods to deduce bone fragment poses from post-op plain radiographs. This approach (Figure 9) takes

advantage of our recent work that has involved aligning 3D bone fragment models (a byproduct of the fracture severity

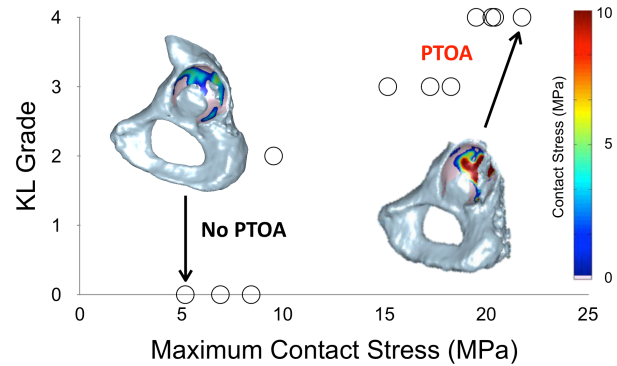


**Figure 7.** KL grade was highly correlated with maximum contact stress at > 24-month follow-up for these patients with IAFs of the acetabulum.

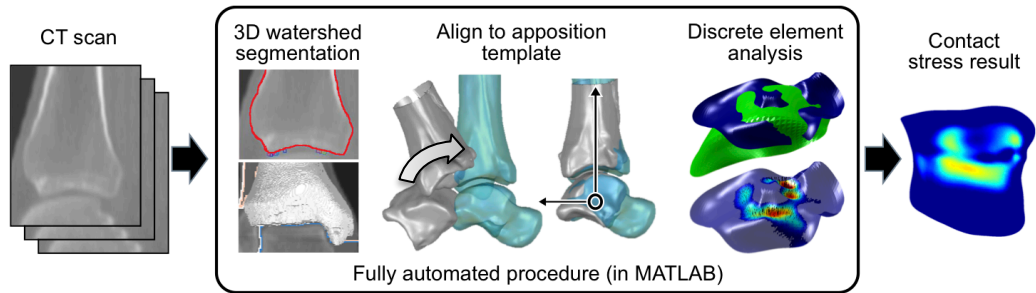


**Figure 8.** Schematic of fully automated procedure for determining habitual contact stress exposure in a given articular fracture reduction, with geometry extracted from CT scan data.

assessments) to match their projective pose captured on intra-op 2D fluoroscopic images. As we advance these methods, for validation we will rely on existing case data for which post-op CTs have already been segmented and contact stress analysis performed. The output from these methods is the pose of the assembled fragments, which together constitute the surgically reduced

joint surface. DEA simulations can then be run to provide a cumulative contact stress exposure estimate to be further considered as a predictor of PTOA risk.

**Major Task 3 (subject identification)** is underway, and we continue screening the trauma registry (DoDTR) to identify and enroll subjects meeting our inclusion criteria. A total of 68 subjects have been identified and enrolled to date.

**Major Task 4 (CT calculations)** is underway, and CDs containing de-identified CT data are being sent from Site 2 to Site 1. As cases arrive at Site 1, we are performing calculations of injury severity and/or post-reduction contact stress. So far, the imaging data for 42 subjects have been forwarded to Iowa for analysis, with another 16 subjects identified and their imaging studies requested. We have completed fracture severity analysis of 20 cases so far (15 tibial pilon fractures and 5 plateau fractures).

- CT studies (de-identified) transferred to Iowa for inspection --- 01-11-2015
- Additional CT studies transferred to Iowa for inspection and analysis --- 30-03-2016
- Fracture severity assessment completed on first subject in the study --- 08-06-2016

## Detailed report of progress on Major Task 4

### *Early results of fracture severity assessment in military subjects*

Because only a limited number of cases have been analyzed to date, only summary statistics are provided here. Comparisons between different fracture types and development of PTOA predictive relationships will need to wait until a substantially larger number of cases are analyzed with clinical outcomes collected. The range of fracture energies measured for the 5 tibial plateau fractures was 4.3-36.5J. The range of fracture energies for the 15 tibial pilon fractures was 2.0-28.7J. The fracture energies (mean $\pm$  standard deviation) of the plateau fractures were 17.2 $\pm$  12.6J, and they were 11.2 $\pm$  8.2J for the pilon fractures. The range of articular fracture edge lengths measured for tibial plateau fractures was 101.1-315.9mm. The range of articular fracture edge lengths for pilon fractures was 18.5-151.5mm. The articular fracture edge lengths (mean  $\pm$  standard deviation) of the plateau fractures were 214.5  $\pm$  92.2mm, and they were 105.7  $\pm$  34.6mm for the pilon fractures. The military fracture cases that we have analyzed to date have fracture energies (Figure 10) and articular fracture edge lengths comparable to those that we measured in the civilian population.

**Major Tasks 5 (PTOA radiographic frequency) and 6 (PTOA symptoms and quality of life)** are just beginning to be addressed, but all indications are that we should be able to proceed with our remaining major tasks as originally planned.

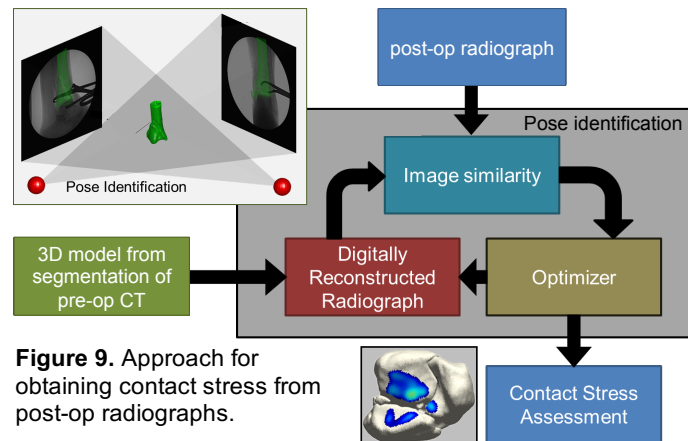


**Figure 9.** Approach for obtaining contact stress from post-op radiographs.

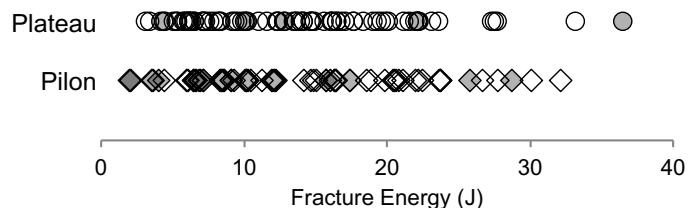


**Figure 10.** Fracture energies for all civilian patients (open symbols) and military patients (closed symbols) plotted on the same chart show similar ranges of severity.

*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. 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. This past year, Mr. Dibbern received a fellowship that enabled him to attend the ten-day Image Based Biomedical Modeling (IBBM) Summer Course offered by the Scientific Computing Institute at the University of Utah.

*How were the results disseminated to communities of interest?*

Nothing to Report

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

In the coming quarter, work will continue identifying and enrolling subjects in the study at the SAMMC site. Analysis will be ongoing as relevant imaging data continue to be received in Iowa. It may be valuable for Dr. Anderson and/or Mr. Dibbern to travel to the SAMMC site during the next quarter to ensure that work proceeds as planned. During this coming quarter, we will be additionally starting work on **Major Task 5**, which involves identifying, finding, and grading follow-up radiographs for PTOA status (KL grading).

#### **4. Impact**

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

Nothing to Report

*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*

During the past year, an issue arose in that MEDCOM had placed restrictions on CD burning of medical imaging data that threatened delays in our work. Fortunately, Dr. Rivera and her team as SAMMC quickly resolved the issue and we are now successfully transferring data.

*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. Kempton LB, Dibbern KA, Anderson DD, Morshed S, Higgins TF, Marsh JL, McKinley TO. Objective metric of energy absorbed in tibial plateau fractures corresponds well to clinician assessment of fracture severity. J Orthop Trauma 2016, May 26;30(10):551-6. Federal support acknowledged.
2. Dibbern K, Kempton LB, Higgins TF, Morshed S, McKinley TO, Marsh JL, Anderson DD. Fractures of the tibial plateau involve similar energies as the tibial pilon but greater articular surface involvement. J Orthop Res ‘Early View’ [dx.doi.org/10.1002/jor.23359](https://doi.org/10.1002/jor.23359). Federal support acknowledged.

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

Nothing to Report

### ▪ Other publications, conference papers, and presentations.

1. Kempton LB, Dibbern K, Anderson DD, Morshed S, Higgins T, Marsh JL, McKinley T. Objective metric of energy absorbed in tibial plateau fractures corresponds well to clinician assessment of fracture severity. 31st Annual Meeting of the Orthopaedic Trauma Association, October 7-10, 2015, San Diego, CA. (\*)
2. Dibbern KN, Kempton LB, Higgins TF, McKinley TA, Marsh JL, Anderson DD. Energy absorbed in fracturing is similar in tibial plateau and pilon fractures over a full spectrum of severity. 83rd Annual Meeting of the American Academy of Orthopaedic Surgeons, March 1-5, 2016, Orlando, FL. (\*)
3. Kempton LB, Dibbern K, Anderson DD, Morshed S, Higgins T, Marsh JL, McKinley T. CT-based metric of tibial plateau fracture energy corresponds well to clinician assessment of fracture severity. 83rd Annual Meeting of the American Academy of Orthopaedic Surgeons, March 1-5, 2016, Orlando, FL. (\*)
4. Dibbern KN, Kempton LB, McKinley TA, Higgins TF, Marsh JL, Anderson DD. Quantifying tibial plateau fracture severity: Fracture energy agrees with clinical rank

ordering. 62nd Annual Meeting of the Orthopaedic Research Society, March 5-8, 2016, Orlando, FL. (\*)

5. Dibbern KN, Higgins TF, Kempton LB, McKinley TA, Marsh JL, Anderson DD. Objective fracture energy assessment of tibial plateau fractures loosely corresponds to Schatzker classification. 62nd Annual Meeting of the Orthopaedic Research Society, March 5-8, 2016, Orlando, FL. (\*)
6. Rao K, Dibbern KN, Phisitkul P, Marsh JL, Anderson DD. Relating fracture severity to post-traumatic osteoarthritis risk after intra-articular calcaneal fractures. 62nd Annual Meeting of the Orthopaedic Research Society, March 5-8, 2016, Orlando, FL.
7. Mosqueda JM, Dibbern KN, Willey MC, Marsh JL, Anderson DD. Elevated contact stress after surgical reduction of acetabular fractures correlates with progression to post-traumatic osteoarthritis. 40th Annual Meeting of the American Society of Biomechanics, August 2-5, 2016, Raleigh, NC.
8. Dibbern KN, Kempton LB, Higgins TF, McKinley TO, Marsh JL, Anderson DD. Clinical fractures of the tibial plateau involve similar energies as the tibial pilon. 40th Annual Meeting of the American Society of Biomechanics, August 2-5, 2016, Raleigh, NC. (\*)
9. Rao K, Dibbern KN, Phisitkul P, Marsh JL, Anderson DD. Post-traumatic OA risk relative to intra-articular calcaneal fracture severity. 32nd Annual Meeting of the Orthopaedic Trauma Association, October 5-8, 2016, National Harbor, MD.
10. Dibbern KN, Drew AM, Anderson DD. A universally applicable, objective CT-based method for quantifying articular fracture severity. 63rd Annual Meeting of the Orthopaedic Research Society, March 19-22, 2017, San Diego, CA.
11. Dibbern KN, Willey MC, Phisitkul P, Glass NA, Marsh JL, Anderson DD. Fracture severity predicts OA risk following intra-articular fractures. 2017 OARSI World Congress on Osteoarthritis, April 27–30, 2017, Las Vegas, Nevada.

*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

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: Kevin Dibbern, MS

Project Role: Graduate Research Assistant

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**

Journal publications and abstracts from the past year (please see above Products for a complete listing) are attached as appendices.

# Objective Metric of Energy Absorbed in Tibial Plateau Fractures Corresponds Well to Clinician Assessment of Fracture Severity

Laurence B. Kempton, MD,\* Kevin Dibbern, BS,† Donald D. Anderson, PhD,‡ Saam Morshed, MD,‡ Thomas F. Higgins, MD,§ J. Lawrence Marsh, MD,† and Todd O. McKinley, MD\*

**Objectives:** Determine the agreement between subjective assessments of fracture severity and an objective computed tomography (CT)-based metric of fracture energy in tibial plateau fractures.

**Methods:** Six fellowship-trained orthopaedic trauma surgeons independently rank-ordered 20 tibial plateau fractures in terms of severity based on anteroposterior and lateral knee radiographs. A CT-based image analysis methodology was used to quantify the fracture energy, and agreement between the surgeons' severity rankings and the fracture energy metric was tested by computing their concordance, a statistical measure that estimates the probability that any 2 cases would be ranked with the same ordering by 2 different raters or methods.

**Results:** Concordance between the 6 orthopaedic surgeons ranged from 82% to 93%, and concordance between surgeon severity rankings and the computed fracture energy ranged from 73% to 78%.

**Conclusions:** There is a high level of agreement between experienced surgeons in their assessments of tibial plateau fracture

severity, and a slightly lower agreement between the surgeon assessments and an objective CT-based metric of fracture energy. Taken together, these results suggest that experienced surgeons share a similar understanding of what makes a tibial plateau fracture more or less severe, and an objective CT-based metric of fracture energy captures much but not all of that information. Further research is ongoing to characterize the relationship between surgeon assessments of severity, fracture energy, and the eventual clinical outcomes for patients with fractures of the tibial plateau.

**Key Words:** tibial plateau fracture, fracture energy, quantifying fracture severity

(*J Orthop Trauma* 2016;30:551–556)

## INTRODUCTION

Fracture severity is commonly assessed by treating orthopaedic surgeons to determine prognosis and decide optimal treatment. Outcomes of intraarticular fractures are influenced by multiple patient, surgeon, and injury factors. The location of a fracture and its morphology, the quantity of articular surface involvement, and the extent of acute mechanical damage all play a role in defining the severity of a fracture. Fracture "severity" spans a spectrum from low to high. Low-severity fractures have characteristics such as minimal displacement or comminution and are thought to have an excellent prognosis with nonoperative treatment. High-severity fractures have characteristics like extensive displacement and comminution and are generally indicated for operative treatment with good to fair prognosis.

These indices, taken together, clearly indicate individual injury specificity. Orthopaedic surgeons formulate treatment strategies based largely on subjective criteria and clinical experience while accounting for patient-specific demographic and medical conditions. However, subjective methods of fracture assessment such as morphology and classification are often poorly reproducible among orthopaedic surgeons and are inherently unreliable.<sup>1–3</sup> There is a risk that relying on such methods may lead to poorly conceived treatment algorithms because they are not grounded in objective data.

The greater the amount of energy dissipated in the creation of a fracture (ie, the fracture energy), the greater the fracture severity. Accurate and reliable measures of the fracture energy can provide objective data for orthopaedic surgeons to use in making treatment decisions and predicting prognosis.

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Presented in part at the Annual Meeting of the Orthopaedic Trauma Association, October 9, 2015, San Diego, CA.

Thomas Higgins is a member of the Board of Directors of the OTA, has stock ownership in Orthogrid and Summit Med Ventures, and is a paid consultant for DePuy Synthes. Todd McKinley is a paid consultant for Bioventus. The remaining authors report no conflict of interest.

Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site ([www.jorthotrauma.com](http://www.jorthotrauma.com)).

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Previous investigations have demonstrated that objective computed tomography (CT)-based measures of fracture energy in tibial pilon fractures correlate with (1) surgeon assessment of injury severity and (2) 2-year radiographic and functional outcomes.<sup>4,5</sup> In this work, we explored whether this technique of objective fracture energy measurement could also be used to stratify the severity of tibial plateau fractures in a manner that would agree with expert opinions of fracture severity. Specifically, we hypothesized that an objective CT-based measure of fracture energy would correspond to subjective surgeon assessment of fracture severity.

## MATERIALS AND METHODS

A fellowship-trained orthopaedic trauma surgeon (TOM) purposefully selected 20 cases from a series of 50 consecutive tibial plateau fractures to represent a full spectrum of fracture severity and to avoid having multiple fractures cluster around a common level of severity. Fracture classifications included orthopaedic trauma association (OTA) 41-B3 and 41-C3, reflecting the use of CT in assigning classifications and a heavy emphasis on articular surface involvement and depression.<sup>6</sup> Patients sustaining the fractures ranged in age from 18 to 70 years old. There were 12 males and 8 females. Our Institutional Review Board approved use of the patient data. See **Table, Supplemental Digital Content 1** (<http://links.lww.com/BOT/A715>) for a summary of demographic information.

Six fellowship-trained orthopaedic trauma surgeons from 4 separate institutions independently rank-ordered the fractures in order of severity based on the appearance of the fractures on AP and lateral knee radiographs. The only instructions given to the raters were to rank the cases in order of least to most severely injured. Subjectively, they used the number and size of fragments, the amount and direction of displacement, percentage of articular

surface involved, and whatever other features they felt were important based on their clinical experience. Raters were blinded to independently obtain CT-derived data and patient information.

A previously validated CT-based image analysis approach was used to quantify the fracture energy based on measurement of the fracture-liberated surface area and accounting for bone density. This method has been shown to be accurate in calculating fracture energy (ie, the amount of energy dissipated in fracturing the bone),<sup>7,8</sup> but the extent of its clinical utility is still under investigation. Fracture energy is expressed in the units of Joules (J), which are equivalent to Newton-meters or  $\text{kg}\cdot\text{m}^2/\text{s}^2$ . Software, custom-written in MATLAB, was used to identify all fracture fragments working from standard-of-care axial CT image data. The surfaces of the fragments were then classified as subchondral, cortical, or interfragmentary based on their associated CT intensities and their local geometric character (surface roughness, curvatures, etc). The surface classifications were subsequently manually confirmed to be accurate, or modified as needed, by an experienced analyst (Fig. 1). The interfragmentary surface areas of all the fracture fragments were summed to provide a single aggregate measure of the fracture-liberated surface area. Bone density values were obtained based on previously established relationships with Hounsfield intensity of CT pixels,<sup>9</sup> and the fracture-liberated surface areas were scaled accordingly to reflect the influence of bone density on the fracture properties. Fracture energy was calculated from a previously validated formula based on the fracture mechanics principle that energy is directly proportional to fracture-liberated surface area scaled by bone density in a brittle solid.<sup>7,8</sup>

We tested our hypothesis by comparing the surgeon rank orderings of fracture severity in this series of tibial plateau fractures with CT-based measurements of fracture energy. The agreement between fracture severity assessments among the surgeons, and between each of the surgeons and the fracture

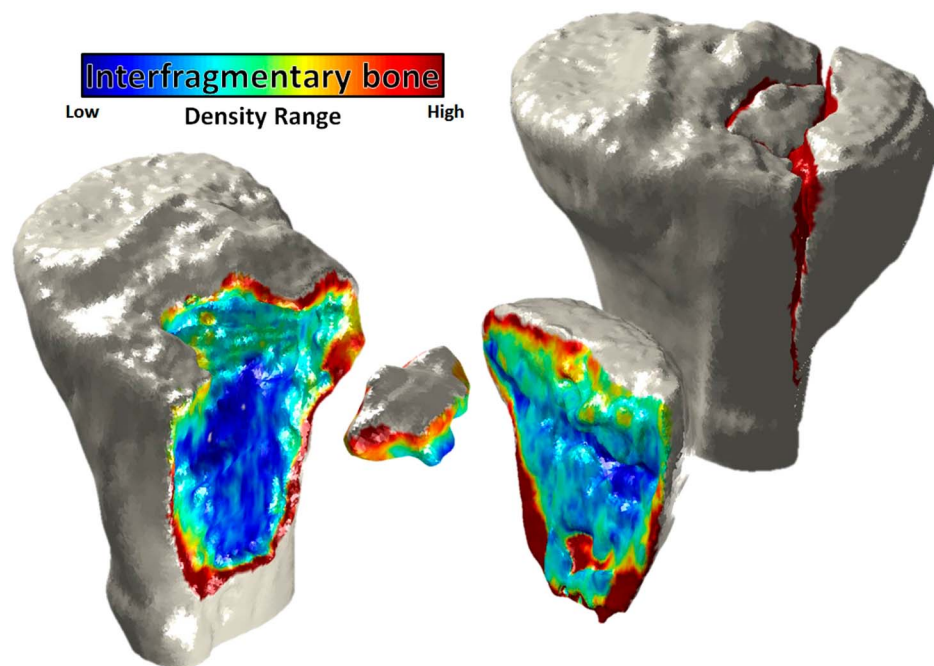


**FIGURE 1.** Custom-written software was used to measure the surface area of the fracture-liberated cancellous (interfragmentary) bone surfaces, colored according to their local density in the exploded view to the left. The fracture-liberated surface area and bone densities were both used to calculate fracture energy. **Editor's Note:** A color image accompanies the online version of this article.

energy metric, was tested by computing their concordance. The injury severity rankings of 2 cases were deemed concordant if the case with the higher ranking of injury severity by 1 rater/metric also had the higher ranking by a second. The concordance was calculated as the number of concordant pairs divided by the total number of possible pairings. This sample-based statistical measure was used to estimate the probability that 2 cases would be ranked with the same ordering. Random assignment of fracture severity by 2 reviewers would be expected to result in a concordance of 0.5 because any case pairing would have a 50% chance of being concordant.

## RESULTS

Fracture energies ranged from 5.5 J to 36.7 J (see **Table, Supplemental Digital Content 1**, <http://links.lww.com/BOT/A715>). There was a high level of agreement between the 6 experienced surgeons in their assessments of tibial plateau fracture severity, with concordances ranging from 82% to 89%, with a mean of 85% (Fig. 2). The concordance between surgeon severity rankings and the fracture energy severity ranking were slightly less high, ranging from 73% to 78%, with a mean of 74%.

Case 19 (as ranked by rater 1) is an example of excellent agreement between orthopaedic surgeons and fracture energy. Severity rankings ranged from 17 to 20 with a fracture energy of 24.5 J (Fig. 3). Substantial articular surface comminution and normal bone density led to a high fracture energy calculation. This feature, as well as substantial fracture displacement, knee dislocation, and bicondylar fracture morphology all contributed to high ranking by the orthopaedic surgeons. Despite the good overall agreement observed between surgeon assessments of fracture severity and the fracture energy metric, there were some notable exceptions. Case 18 demonstrated substantial discrepancy between the objective fracture energy metric and all 6 subjective ratings (Fig. 4). The orthopaedic surgeons all rated this fracture as high in severity, whereas the fracture energy value was modest (11.9 J). The radiographs demonstrate significant fracture malalignment, which would not be reflected in the fracture energy. In contrast, case 7 was a clear outlier with a much higher fracture energy value (17.9 J) relative to the low severity rank assigned by all 6 raters (Fig. 5). The common “split-depression” (OTA 41-B3) was typically deemed lower severity by all surgeons, but closer inspection of the sagittal CT section demonstrates significant comminution leading to a higher fracture energy measurement.

## DISCUSSION

The purpose of this study was to determine whether a CT-based fracture energy metric could provide an objective, quantifiable measure of tibial plateau fracture severity by comparing it to the current gold standard, subjective expert surgeon opinion. We found a high level of agreement (85%) regarding fracture severity among the 6 orthopaedic trauma subspecialists. The level of agreement between surgeon assessments of fracture severity and fracture energy was 74%, suggesting that fracture energy has clinical relevance.

These results demonstrate that fracture energy reasonably mirrors expert opinion regarding the relative fracture severity over a full spectrum of tibial plateau fractures. This builds on the findings of previous investigations of tibial pilon fractures and shows that fracture energy may be used as a measure of injury severity in other intraarticular fractures as well.

The two major benefits of using fracture energy rather than clinician assessment are its ability to physically quantify severity and its objective nature. Quantifying fracture energy allows for distribution of fracture severity over continuous scales ranging from the entire spectrum of injury severity to subtle differences not appreciated by clinical assessment. In contrast, current classification schemes place fractures into one of several categories and often do not distinguish between substantially different injuries. Objectivity in calculating fracture energy is also valuable because it prevents clinician bias and disagreement resulting from subjective assessments and ensures reproducibility of calculations through rigorous algorithms.

The Schatzker classification and OTA classification are 2 common subjective methods that categorize tibial plateau fractures and convey information about fracture severity. The

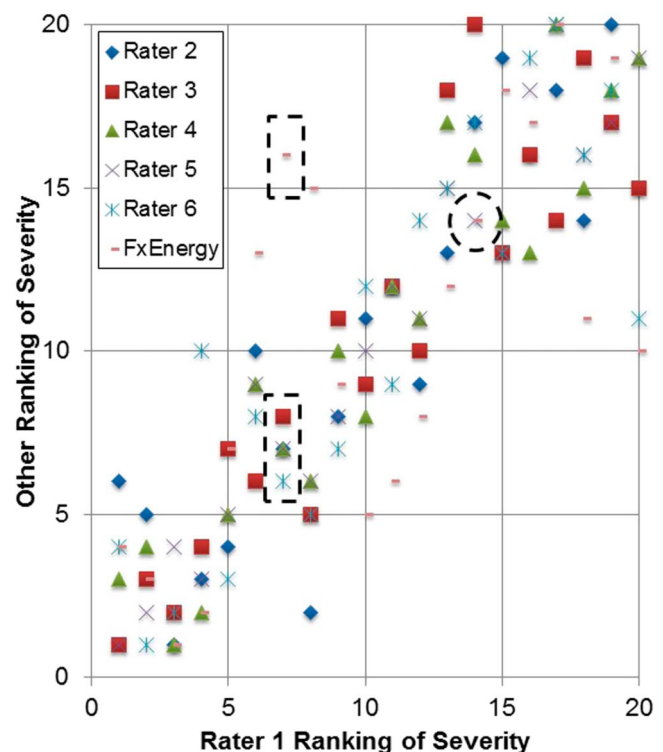


**FIGURE 2.** Representative rank ordering of fracture severity by 6 orthopaedic trauma surgeons and by fracture energy. The y-axis represents severity ranking as assigned by raters 2–6 and according to the calculated fracture energy. The x-axis represents the rank ordering of rater 1. As an example, there was high agreement between rater 1 and raters 2 through 6 at rater-1 injury number 7, but this fracture’s rank according to fracture energy calculation was much higher (black dashed boxes). At rater-1 injury number 14, the rank according to fracture energy was the same as the rank assigned by raters 1 and 5 (dashed circle). **Editor’s Note:** A color image accompanies the online version of this article.



**FIGURE 3.** Example of high level of agreement between orthopaedic surgeons and fracture energy calculation. These AP and lateral knee radiographs demonstrate a bicondylar tibial plateau fracture with substantial articular surface comminution and displacement and an associated knee dislocation.

interobserver reliability of assigning fractures within these 2 classifications based on radiographs ranges from 0.38 to 0.47 and from 0.36 to 0.43 (Kappa statistic), respectively.<sup>1–3,10</sup> When the classifications are based on CT, the reliabilities increase to 0.76 and 0.73, respectively.<sup>10</sup> Although concordance values cannot be directly compared with correlation, our concordance rates of 73%–78% fracture energy and surgeon ranking suggest a similar or better level of agreement relative to current classification strategies. Although this study does not necessarily support incorporating fracture energy calculations into clinical practice, it demonstrates clinical relevance of fracture energy. Therefore, fracture energy can be used to quantify injury severity as an objective, continuous variable in studies comparing 2 groups of fractures to determine extent of group similarity. This is superior to

common methods of comparing severity between groups using fracture classification.

It may also be that fracture energy predicts outcomes as a function of treatment. Perhaps excellent outcomes can be expected after nonoperative treatment of a low-severity fracture (fracture energy of 6 J), whereas poor outcomes with nonoperative treatment (and good outcome with operative treatment) can be expected for a high-severity fracture (fracture energy of 30 J). If that were the case, then measurement of fracture energy would be helpful to determine operative indications, as well as predict future patient function.

There are several inherent inaccuracies and discrepancies in CT-based measurements and surgeon observations. First, the fracture energy calculation was based solely on fracture-liberated surface area and bone density. It does not



**FIGURE 4.** Example of high clinician ranking but modest fracture energy. These AP and lateral knee radiographs and a representative coronal CT cut demonstrate osteopenia and substantial metaphyseal impaction without many separate pieces of comminution. The ranking surgeons considered these factors in their assessment of severity, but the fracture energy calculation did not.



**FIGURE 5.** Example of high fracture energy but low surgeon ranking. These AP and lateral knee radiographs and representative sagittal CT cut demonstrate a fracture that surgeons ranked low in severity because of minimal comminution and depression at the weight-bearing portion of the articular surface and very little overall fracture displacement. However, comminution throughout the posterior central portion of the tibial plateau substantially contributed to an increased fracture energy calculation.

yet account for other fracture features observed by surgeons, such as fracture displacement, malalignment (Fig. 4), fracture morphology (eg, extent of articular surface comminution vs. metaphyseal comminution), or the ease of fixing the fracture, all of which may influence outcomes. Decreased bone density also directly reduces objective energy measurements. In contrast, it is possible that surgeons examining radiographs would ascribe a higher severity to an osteopenic fracture based on fracture fixation difficulties often encountered in such injuries. This would lead to higher severity ranking by surgeons compared with lower fracture energy calculations. Another factor leading to higher surgeon ranking of severity relative to fracture energy is that the surface area metric is based on brittle material assumptions<sup>11</sup> and does not account for plastic deformation. Therefore, impacted metaphyseal and articular surface fragments, which often have significant compaction of underlying trabecular bone, may have absorbed higher levels of energy than were measured. This could lead to an artificially lower fracture energy calculation, particularly in fractures with significant articular surface comminution. Finally, a limitation of the study unrelated to the technique for measuring fracture energy is that the orthopaedic surgeons judged fracture severity based solely on plain radiographs, but the fracture energy calculation was based on CT data. Therefore, there were likely instances in which certain fracture characteristics not appreciated on radiographs may have led to underestimation of fracture severity by surgeon assessment.

Fracture displacement, undeniably one of the most important clinical assessment criteria, was not included in the fracture energy metric. This was because regression analysis in our previous work<sup>7</sup> identified fracture energy and articular comminution as statistically significant post-traumatic osteoarthritis predictors ( $P < 0.01$ ), but not fragment displacement ( $P = 0.35$ ). Actually, fracture energy and fracture displacement were only loosely linked in that work. This may partly be because

injury CT scans are often obtained after the application of a temporary external distractor.

This work is a preliminary interrogation of a novel method to yield objective evidence that may eventually prove useful to guide treatment decisions. However, there are no data yet from our study that correlate fracture energy and clinical outcomes. Surgeon rank-order assessment of fracture severity is a reasonable subjective index but has no objective jurisdiction in predicting outcomes. In this study, we chose to use this subjective measure as there is currently no other standard against which to compare fracture energy. Further investigation is ongoing to determine whether quantified relationships between objective fracture energy indices and objective measurements of clinical outcomes can be established.

In conclusion, an objective CT-based measurement of fracture energy demonstrated good concordance with fellowship-trained orthopaedic trauma surgeon subjective assessment of injury severity in tibial plateau fractures, adding to previous work reporting similar findings for tibial pilon fractures. Ongoing investigation will determine the clinical utility of these measurements.

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# Fractures of the Tibial Plateau Involve Similar Energies as the Tibial Pilon but Greater Articular Surface Involvement

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**ABSTRACT:** Patients with tibial pilon fractures have a higher incidence of post-traumatic osteoarthritis than those with fractures of the tibial plateau. This may indicate that pilon fractures present a greater mechanical insult to the joint than do plateau fractures. We tested the hypothesis that fracture energy and articular fracture edge length, two independent indicators of severity, are higher in pilon than plateau fractures. We also evaluated whether clinical fracture classification systems accurately reflect severity. Seventy-five tibial plateau fractures and 52 tibial pilon fractures from a multi-institutional study were selected to span the spectrum of severity. Fracture severity measures were calculated using objective CT-based image analysis methods. The ranges of fracture energies measured for tibial plateau and pilon fractures were 3.2–33.2 Joules (J) and 3.6–32.2 J, respectively, and articular fracture edge lengths were 68.0–493.0 mm and 56.1–288.6 mm, respectively. There were no differences in the fracture energies between the two fracture types, but plateau fractures had greater articular fracture edge lengths ( $p < 0.001$ ). The clinical fracture classifications generally reflected severity, but there was substantial overlap of fracture severity measures between different classes. Similar fracture energies with different degrees of articular surface involvement suggest a possible explanation for dissimilar rates of post-traumatic osteoarthritis for fractures of the tibial plateau compared to the tibial pilon. The substantial overlap of severity measures between different fracture classes may well have confounded prior clinical studies relying on fracture classification as a surrogate for severity. © 2016 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. *J Orthop Res*

**Keywords:** tibial plateau; tibial pilon; fracture severity; post-traumatic OA

Post-traumatic osteoarthritis (PTOA) commonly occurs following a variety of joint injuries. Articular fractures of the lower extremity are particularly at risk of PTOA, and they often result from similar injury mechanisms. Despite similarities in the injuries, PTOA develops in 23–44% of tibial plateau fractures before 15 years<sup>1,2</sup> but in as many as 74% of tibial pilon fractures.<sup>3</sup> The reasons for this difference are not well understood. It is known that outcomes of articular fractures are influenced by the severity of the damage sustained at the time of injury and as a result of abnormal loading associated with changes to articular congruity, joint alignment, and joint stability after healing.<sup>4–6</sup>

The primary goals in treating articular fractures are to restore limb alignment and precisely reduce any articular displacement to decrease the likelihood of PTOA. The severity of the fracture correlates highly with the risk of PTOA, so treating surgeons have adopted fracture severity assessment methods to aid in their treatment decision-making. However, conventional systems for classifying fractures and their severity are highly subjective, have poor reliability, and cannot reliably predict risk of PTOA.<sup>7–13</sup>

The damage sustained at the time of injury can be objectively assessed through physical manifestations of the fracture severity: the amount of energy involved in fracturing a bone (i.e., the fracture energy) and the amount of articular surface involvement. It has been demonstrated in fractures of the tibial pilon that these fracture severity metrics significantly correlate with PTOA incidence.<sup>14–16</sup> This provides a possible explanation for differences found in the rates of PTOA development in tibial pilon and plateau fractures; that is, greater energy is absorbed or articular surface involved in creating tibial pilon fractures compared to plateau fractures.

In this study, an objective CT-based methodology for measuring fracture energy and articular surface involvement was used to explore the hypothesis that fracture severity metrics are higher in pilon fractures compared to plateau fractures. In addition, we assessed the relationship between the fracture severity measures and traditional categorical fracture classification systems to determine how well the classifications reflected severity.

## METHODS

Fellowship-trained orthopedic trauma surgeons enrolled 75 patients with tibial plateau fractures spanning an entire spectrum of severity in this multi-institutional level III diagnostic study. These were compared with 52 patients having sustained tibial pilon fractures, enrolled in a similar manner. An Institutional Review Board approved use of the patient data, collected during standard-of-care clinical treatment.

Fracture severities were calculated using a previously validated, objective, CT-based image analysis methodology.<sup>15,17</sup>

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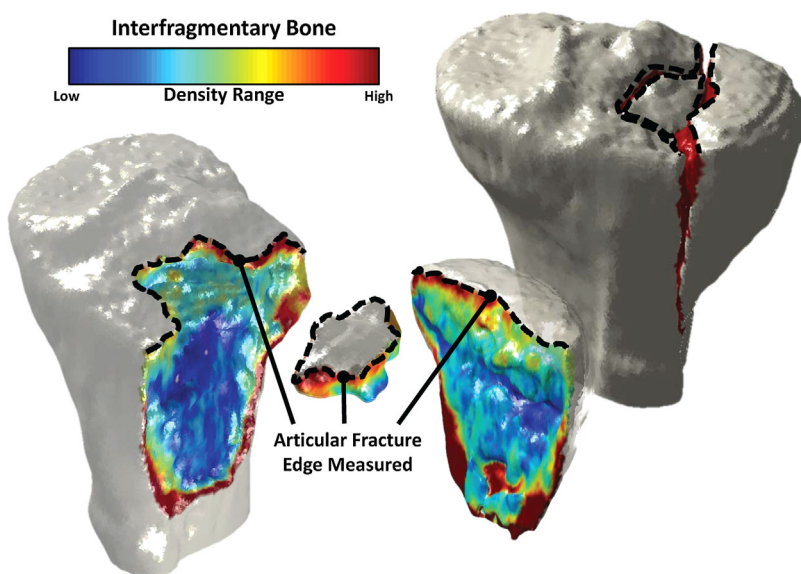


**Figure 1.** Custom-written software was used to measure surface area of pre-injury cortical and subchondral bone surfaces and post-injury-exposed interfragmentary bone surfaces. The fracture-liberated surface area and the bone densities across that surface were used to calculate fracture energy. The length of the edge between the subchondral and interfragmentary bone surfaces (the articular fracture edge length—highlighted with dashed black lines) was used to quantify articular surface involvement.

This technique quantifies fracture energy based upon measurement of the fracture-liberated surface area, accounting for variations in bone density over the interfragmentary surfaces (Fig. 1). Software, custom-written in MATLAB (MathWorks, Inc., Natick, MA), was used to identify all fracture fragments working from CT scan data. The surfaces of the fragments were then classified as intact cortical, subchondral, or de novo interfragmentary based upon their CT intensities and local geometric character (surface roughness, curvatures, etc.). The surface classifications were then manually evaluated and modified as needed by an expert analyst (Fig. 1). The interfragmentary surface areas of all of the fracture fragments were then summed to provide a measure of the fracture-liberated surface area. Bone densities were estimated from the CT Hounsfield intensities at each CT scan pixel using previously established relationships.<sup>18,19</sup> The location-specific bone density was then used to appropriately scale fracture-liberated surface areas by density-dependent energy release rates to obtain the fracture energy.<sup>15–17</sup> An additional measure reflecting the amount of articular surface involvement was derived by quantifying the articular fracture edge length, defined as the length of the edge at the intersection between interfragmentary and subchondral bone surfaces.

Fracture energies and articular fracture edge lengths were obtained for all pilon and plateau fractures enrolled in the study. A *t*-test statistic was used to test the hypothesis that the fracture severity characteristics differed between the two fracture locations. In order to gain further insight regarding any differences in the two fracture types, cases of similar fracture energies were qualitatively evaluated for energies at the low end, at an intermediate value, and at the high end of the fractures studied.

The fractures were also characterized using two different fracture classification systems, based upon consensus evaluation by three fellowship-trained orthopedic traumatologists (LBK, TOM, JLM). The Schatzker classification system was developed as a method for identifying groups of tibial plateau fractures with distinct pathomechanical and etiological factors.<sup>20</sup> This system has well-established clinical utility in guiding treatments and predicting outcomes.<sup>21</sup> The AO/OTA classification system, on the other hand, seeks to categorize fractures based upon their morphological characteristics in order of increasing complexity and severity, where severity “implies anticipated difficulties of treatment, the likely complications, and the prognosis.”<sup>22–24</sup> Where the Schatzker classification seeks to categorize intra-articular fractures of the tibial plateau alone, the AO/OTA classification system is applicable to a broader set of fractures. The fracture energies computed for fractures in different Schatzker and AO/OTA classes were compared to test how well the classification systems reflected severity.

## RESULTS

The range of fracture energies measured for tibial plateau fractures was 3.2–33.2 Joules (J). The range of fracture energies for pilon fractures was 3.6–32.2 J (Fig. 2a). The fracture energies (mean  $\pm$  standard deviation) of the plateau fractures were  $13.3 \pm 6.8$  J, and they were  $14.9 \pm 7.1$  J for the pilon fractures. The distribution of energies for each fracture type was similar. Although these types of fractures are highly idiosyncratic, the smallest fragments in the plateau fractures tended to be smaller than those in the pilon fractures.

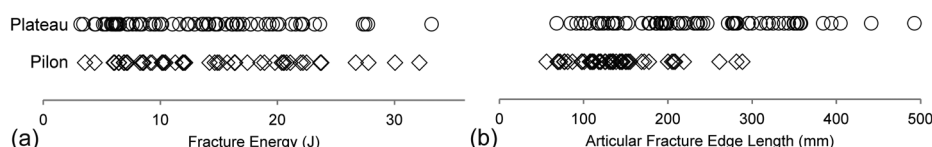


**Figure 2.** Tibial plateau and pilon (a) fracture energy and (b) articular fracture edge length values distributed over a full spectrum of injury severity.

The range of articular fracture edge lengths measured for tibial plateau fractures was 68.0–493.0 mm. The range of articular fracture edge lengths for pilon fractures was 56.1–288.6 mm (Fig. 2b). The articular fracture edge lengths (mean  $\pm$  standard deviation) of the plateau fractures were  $231.4 \pm 94.7$  mm, and they were  $138.1 \pm 54.9$  mm for the pilon fractures. Fractures of the tibial plateau had greater articular fracture edge lengths than those of the pilon ( $p < 0.001$ ).

Qualitative comparisons of tibial plateau and pilon fractures with low, intermediate, and high fracture energies showed similarities in the number and size of the fragments in each range and supported the observations regarding the amount of articular surface involvement (Fig. 3). The lower energy fractures were selected at 3.2 J and 3.6 J for the plateau and pilon, respectively. The lower energy pilon fracture had two fragments, while the lower energy plateau fracture had three. The largest two fragments on each were similar in size between the plateau and pilon, while the third fragment seen on the plateau was much

smaller. The intermediate energy fractures were selected at 14.2 J and 14.9 J for the plateau and pilon, respectively. Again, similar quantities and sizes of fragments were found for the two different anatomical sites. Finally, the higher energy fractures were selected at 27.3 J and 24.6 J for the plateau and pilon, respectively. These higher energy fractures had numerous smaller fragments and involved substantial diaphyseal extension.

Fracture classifications for the plateau injuries ranged from Schatzker I to VI (Table 1). The plateau fractures ranged in AO/OTA class from 41-B1 to 41-C3 and the pilon fractures ranged from 43-B1 to 43-C3 (Table 2). The average fracture energies and articular fracture edge lengths for the most part increased with increasing Schatzker (Fig. 4) and AO/OTA classification (Fig. 5), indicating general agreement between the fracture classes and the severity metrics associated with such fractures. However, the severity metrics varied, in some instances considerably, within individual classes. In addition to the overall fracture

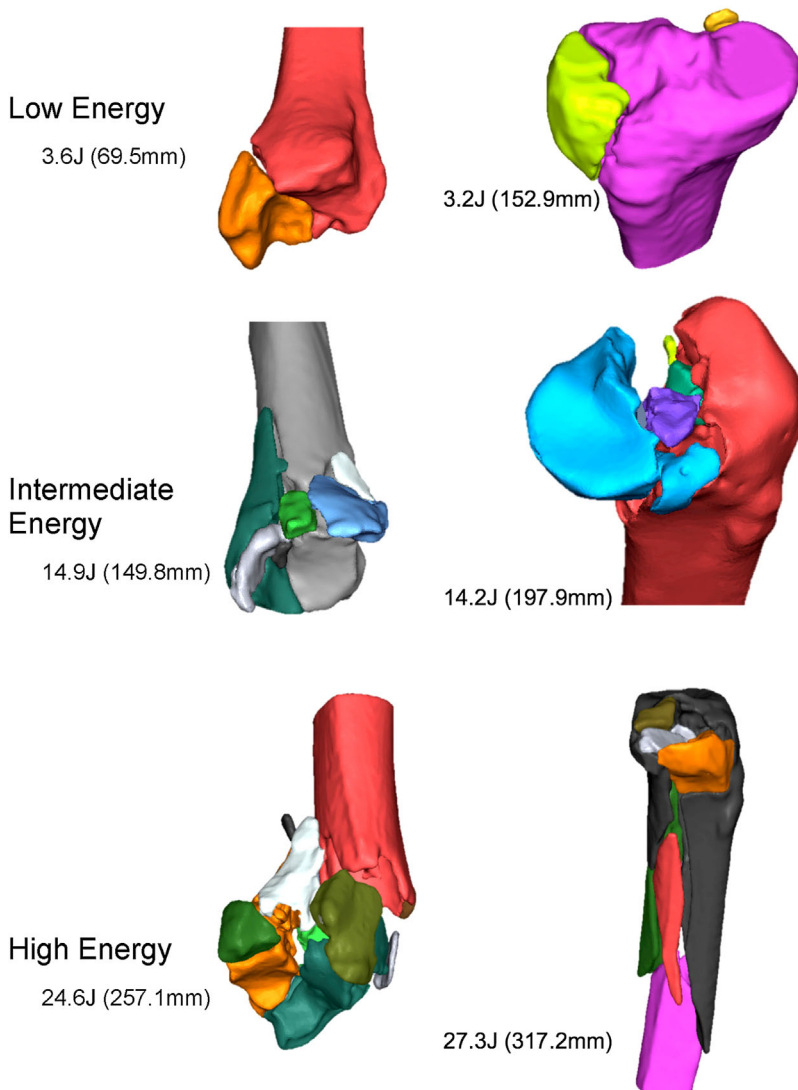


**Figure 3.** Fracture energy comparison between tibial pilon (left) and plateau (right) injuries. Different colors are assigned to individual fragments in these graphical representations. Articular fracture edge length values are shown for reference, in parentheses.

**Table 1.** Distribution of Tibial Plateau Fractures, Fracture Energies, and Articular Fracture Edge Lengths by Schatzker Fracture Classification

| Schatzker Class | Number of Cases | % of Total | Fracture Energy (J) | Articular Fracture Edge Length (mm) |
|-----------------|-----------------|------------|---------------------|-------------------------------------|
| I               | 3               | 4          | 9.3 (6.9)           | 134.6 (40.7)                        |
| II              | 27              | 36         | 8.8 (4.2)           | 227.7 (83.0)                        |
| III             | 0               | 0          | —                   | —                                   |
| IV              | 16              | 21         | 11.9 (4.8)          | 225.3 (92.3)                        |
| V               | 5               | 7          | 13.7 (3.0)          | 247.8 (129.9)                       |
| VI              | 24              | 32         | 19.8 (6.1)          | 253.6 (110.8)                       |

Values are mean (standard deviation).

energies of pilons and plateaus being similar, the ranges and medians of fracture energies for AO/OTA B3 and C3 fractures of pilons and plateaus were also quite similar. The same was not true of articular fracture edge lengths, with the ranges and medians of pilons being substantially smaller than those of plateaus. Finally, the higher fracture classes consistently demonstrated a wider range of fracture severity metric values than was observed for less complex fracture patterns, although there were relatively fewer fractures seen in the less complex categories.

## DISCUSSION

There were no differences in the fracture energies between the pilon and plateau fracture types, but there were differences in the articular fracture edge lengths. Similar injury mechanisms typically lead to these two fractures, and previous studies show a substantially lower incidence of PTOA resulting from tibial plateau fractures compared to pilon fractures. PTOA represents an organ-level injury response that is complex and likely joint-specific. Impact tolerance of the proximal tibia may be explained by differences in joint morphology/anatomy, cartilage thickness, the subchondral bone, inflammatory response after injury, mechanics of joint load distribution, or a variety of other factors.

Differences in size and joint morphology between the tibial plateau and pilon provide possible explanations for differences in PTOA risk. This is consistent with the greater amount of articular surface involvement and comminution seen in the tibial plateau fractures, although greater surface involvement would generally be expected to increase PTOA risk. Another anatomical confounder could stem from the large difference in the size of the articular surfaces between the two joints. The tibial plateau has a significantly larger articulating surface ( $\sim 1,200 \text{ mm}^2$ ) than the tibial pilon ( $\sim 600 \text{ mm}^2$ ).<sup>24,25</sup> The tibio-talar joint could therefore experience a higher energy per unit area transmitted upon fracturing than the tibio-femoral joint. The higher energy per unit area could result in a larger degree of acute chondrocyte damage or death in the pilon when compared to the plateau. This presents an area for future development of the fracture severity measure to include bone or fracture-specific characteristics.

Substantial differences in soft tissue structures could also contribute in multiple ways. The tibial plateau has a dense, load-bearing, fibrocartilaginous meniscus and other substantial soft tissues. It is reasonable to assume that in contrast with the robust bony load bearing in the ankle, the soft tissue support in the knee may aid in preventing post-fracture deterioration, despite similar energies involved in the injuries. Further confounding this possibility is variable/occult comorbidity to these soft tissues associated with fractures of the tibial plateau. Previous studies have demonstrated approximately double the incidence of PTOA of the knee in plateau fractures with meniscectomies compared to those where the meniscus was reconstructed (74% vs. 37%).<sup>26</sup> In the context of surgical fracture reduction, the integrity of the soft tissues around the joint is seldom a focus of attention. Finally, the appeal of using fracture energy to assess severity in this context is that it is an indirect indicator of injury to the articular cartilage, as well as the bone. Ideally, a measure of fracture severity reflects the amount and the distribution of energy transmitted across the articular surface. The larger

**Table 2.** Distribution of Fracture Energies and Articular Fracture Edge Lengths for Tibial Plateau and Pilon Fractures by AO/OTA Fracture Classification

| AO/OTA Class | Plateau         |            |                     |                                     | Pilon           |            |                     |                                     |
|--------------|-----------------|------------|---------------------|-------------------------------------|-----------------|------------|---------------------|-------------------------------------|
|              | Number of Cases | % of Total | Fracture Energy (J) | Articular Fracture Edge Length (mm) | Number of Cases | % of Total | Fracture Energy (J) | Articular Fracture Edge Length (mm) |
| B1           | 4               | 5          | 8.6 (5.8)           | 134.5 (33.2)                        | 5               | 10         | 7.1 (2.2)           | 94.4 (26.8)                         |
| B2           | 2               | 3          | 16.9 (4.6)          | 299.8 (120.1)                       | 1               | 2          | 6.1 (—)             | 120.6 (—)                           |
| B3           | 45              | 60         | 10.1 (4.4)          | 227.9 (88.3)                        | 15              | 29         | 10.2 (5.0)          | 127.1 (38.5)                        |
| C1           | 2               | 3          | 21.4 (0.3)          | 140.8 (79.1)                        | 2               | 4          | 17.5 (14.6)         | 99.6 (1.4)                          |
| C2           | 5               | 7          | 17.5 (7.6)          | 220.1 (100.5)                       | 12              | 23         | 19.7 (6.3)          | 124.1 (61.0)                        |
| C3           | 17              | 23         | 20.3 (6.0)          | 276.7 (110.6)                       | 17              | 33         | 18.1 (5.1)          | 169.1 (52.8)                        |

Values are mean (standard deviation).

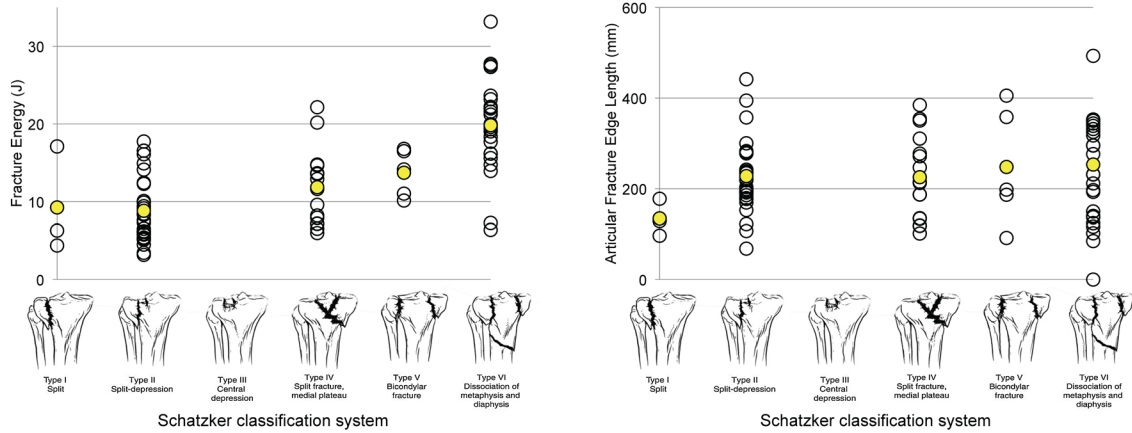


**Figure 4.** Range of fracture energies and articular fracture edge lengths as they vary over the Schatzker classes of tibial plateau fractures.

the quantity of energy, the more initial cartilage damage and subsequent degeneration would be predicted. Other joint-specific factors influential in this respect include the cartilage thickness and the rigidity of the subchondral and underlying metaphyseal bone. The cartilage of the tibial plateau is significantly thicker (~3mm) than for the tibial pilon (~1.5mm). The intra-tissue strains at the time of injury would therefore be expected to be more severe in the thinner cartilage of the pilon compared to the plateau.

The larger range of fracture energies seen in higher classes of the fracture classifications (C3, Schatzker V and VI) may reflect the fact that more complex and variable injuries make up these classes. However, the higher class fracture patterns were not necessarily more severe (i.e., did not always have higher fracture energies). This suggests that fracture classifications are less reflective of severity for the more complex fracture patterns. A surprisingly wide range of fracture energy was seen for the fracture classifications that we assessed, suggesting that these classifications

are not a reliable surrogate for fracture severity. Combining fracture classification, which categorizes the morphologic characteristics of the fracture, with objective measurement of fracture energy would provide a more complete assessment of articular fractures.

Historically, studies comparing different groups of fractures have used AO/OTA fracture classification to show that the groups had similar fracture characteristics and severity. Perhaps the most useful conclusion from these data is that prior studies failing to demonstrate group equivalence simply by showing no statistical difference in fracture classification type are missing critical information about underlying differences in fracture severity. Assigning “high energy” and “low energy” based on injury mechanism and fracture pattern is largely subjective and fails to sufficiently stratify severity. The data presented in this study provide strong evidence of the utility that fracture energy has in the context of clinical research.

This study is not without limitations. The accuracy of the fracture energy calculations may suffer either

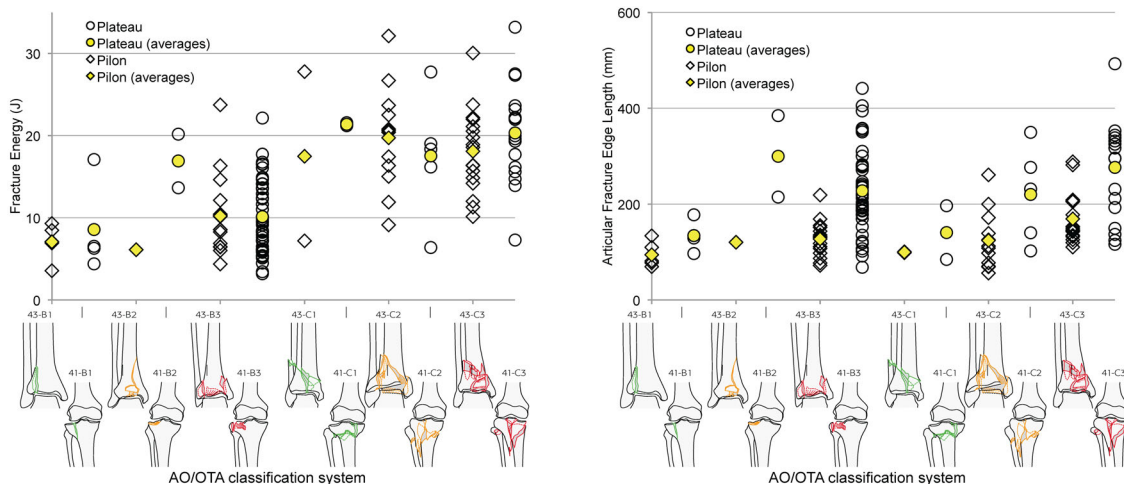


**Figure 5.** Range of fracture energies and articular fracture edge lengths as they vary over the different AO/OTA classes for the tibial plateau and pilon fractures.

when small bone fragments are missed in segmentation from CT or when there is substantial compaction of bone. The volumes of the smallest fragments segmented were on the order of 10–20 mm<sup>3</sup>. We cannot rule out inaccuracies associated with missing smaller fragments but would not expect for those to contribute appreciably to fracture energy absorption. Bone compaction was not assessed in our measurements but again, given the relatively low density of cancellous bone subject to compaction, it is unlikely that this would introduce substantial inaccuracy. Another limitation is that soft tissue status was not available for inclusion in the assessments of fracture severity. Ultimately, a more robust predictive algorithm may involve not only calculation of fracture energy but also some measure of soft tissue status. A present lack of follow-up data prevented the evaluation of the relationships between fracture severity and outcomes in the plateau and pilon fractures. Establishing these relationships is the objective of ongoing study in these patients, who are all being followed prospectively.

PTOA is a complex disease with many contributing factors. The findings in this study disprove our hypothesis that tibial pilon fractures have a higher energy absorbed than plateau fractures across the spectrum of injury, but they raise new questions about differences in the amount of articular surface involvement. Our results show similar energy absorption profiles with greater articular involvement in the tibial plateau, suggesting that it may be more tolerant of impact injury compared to the distal tibia. This possibility will need to be tested further as longer term outcome data become available for the specific patients analyzed in this study.

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## AUTHORS' CONTRIBUTIONS

All authors made substantial contributions to the research design, data acquisition, and analysis/interpretation of data. K.D., L.K., T.M., J.L.M., and D.D.A. were involved in the drafting of the paper, and all authors provided subsequent critical review. All authors have read and approved the final submitted manuscript.

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## Objective Metric of Energy Absorbed in Tibial Plateau Fractures Corresponds Well to Clinician Assessment of Fracture Severity

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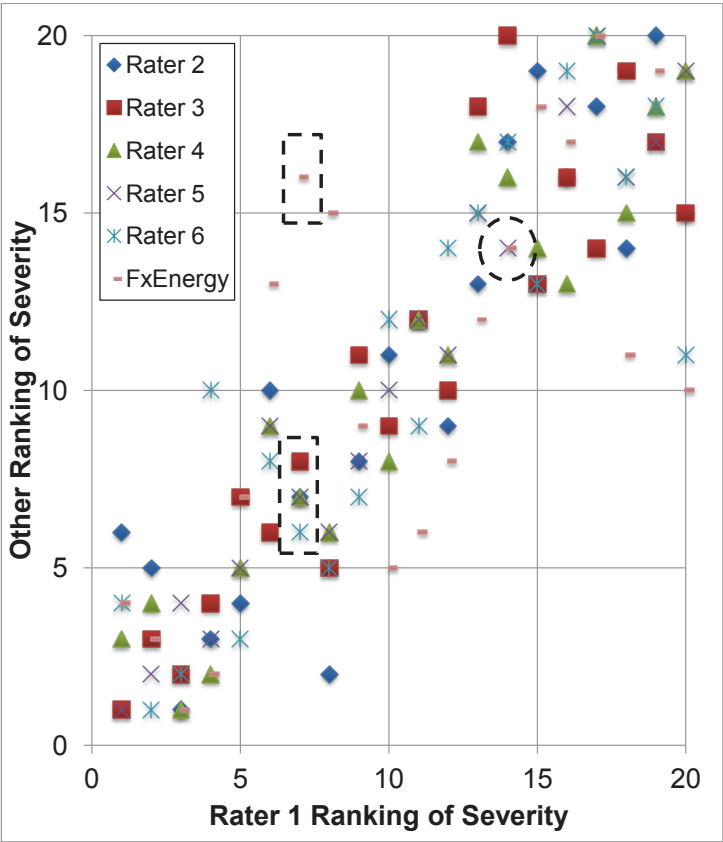
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**Background/Purpose:** Outcomes of intra-articular fractures are influenced both by acute mechanical damage and by residual chronic changes in joint loading. The extent of damage sustained in the acute setting reflects the energy absorbed in creation of the fracture; therefore, fracture energy can be expected to substantially influence clinical outcomes. Previous investigations have demonstrated that objective CT-based quantification of fracture energy in pilon fractures correlates with surgeon assessment of injury severity and 2-year radiographic outcomes. It is not clear whether these findings can be extrapolated to other articular fracture types. In this work, we explored whether this technique of fracture energy measurement could be used to stratify the severity of tibial plateau fractures. Specifically, we hypothesized that a CT-based measure of fracture energy would correspond to subjective surgeon assessment of fracture severity. We tested the hypothesis by comparing surgeon rank ordering of fracture severity for a series of tibial plateau fractures with CT-based measurements of fracture energy.

**Methods:** Twenty fractures were selected from a series of 50 tibial plateau fractures to span a full spectrum of severity. Fracture classification ranged from OTA 41-B1 to 41-C3. Six fellowship-trained orthopaedic trauma surgeons independently rank-ordered the fractures in order of severity using AP and lateral knee radiographs. The only instructions given to the raters were to rank the cases in order of least to most severely injured. Subjectively, they used the number and size of fragments, the amount and direction of displacement, percentage of articular surface involved, and whatever other features they felt were important based on their clinical experience. CT-based image analysis techniques were used to quantify the fracture energy. The software identifies all fracture fragments on CT imaging and calculates the amount of bone surface area liberated by the fracture. The previously validated algorithm incorporates fracture liberated surface area and bone density to provide the fracture energy measurement. The agreement between fracture severity assessments made by the surgeons and the ranking by fracture energy measurement was tested by computing their concordance. A pair of cases' injury severity rankings was deemed concordant if the case with the higher ranking of injury severity for one rater also had the higher ranking for a second rater. Simply put, the rate of concordance is the number of concordant pairs divided by the total number of possible pairings.

**Results:** Concordance between the six orthopaedic surgeons ranged from 82% to 93%. Concordance between surgeon severity ranking and fracture energy ranged from 73% to 78% (Fig. 1).

**Figure 1: Representative rank-ordering of fracture severity by six orthopaedic trauma surgeons and by fracture energy.** The y-axis represents severity ranking as assigned by raters 2-6 and according to the calculated fracture energy. The x-axis represents the rank ordering of rater 1. As an example, there was high agreement between rater 1 and raters 2 – 6 at rater-1 injury number 7, but this fracture’s rank according to fracture energy calculation was much higher (black dashed boxes). At rater-1 injury number 14, the rank according to fracture energy was the same as the rank assigned by raters 1 and 5 (dashed circle).



**Conclusion:** There is a high level of agreement between surgeon assessment of tibial plateau fracture severity and CT-based measurement of fracture energy. In addition, agreement among six surgeons with extensive clinical experience judging injury severity was excellent. Taken together, these results confirm that a CT-based method of calculating fracture energy accurately portrays fracture severity as judged clinically for tibial plateau fractures and provides an objective way to quantify injury severity. In addition, it is likely this tool will be clinically useful as there was excellent surgeon agreement on fracture severity. Further research is ongoing to characterize the relationship between fracture energy and clinical outcomes. Funding: Research reported in this abstract was supported by the National Institute of Arthritis and Musculoskeletal and Skin Diseases of the National Institutes of Health under award number R21AR061808. The research was also aided by a grant from the Foundation for Orthopaedic Trauma.

The FDA has stated that it is the responsibility of the physician to determine the FDA clearance status of each drug or medical device he or she wishes to use in clinical practice.

**Energy Absorbed in Fracturing is Similar in Tibial Plateau and Pilon Fractures Over a Full Spectrum of Severity**

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**INTRODUCTION:** Tibial pilon fractures have a higher rate of post-traumatic osteoarthritis (PTOA) compared to tibial plateau fractures. The reasons for this difference are not understood. Outcomes of articular fractures are influenced by acute damage sustained at the time of injury and residual abnormal loading resulting from changes in congruity, alignment, or stability after healing. One potential explanation for the outcome differences between these two fracture types is that greater energy of injury is absorbed to create tibial pilon fractures compared to plateau fractures. In this study, we utilized a CT-based measurement of fracture energy to explore the hypothesis that fracture energy is consistently higher in pilon fractures compared to plateau fractures.

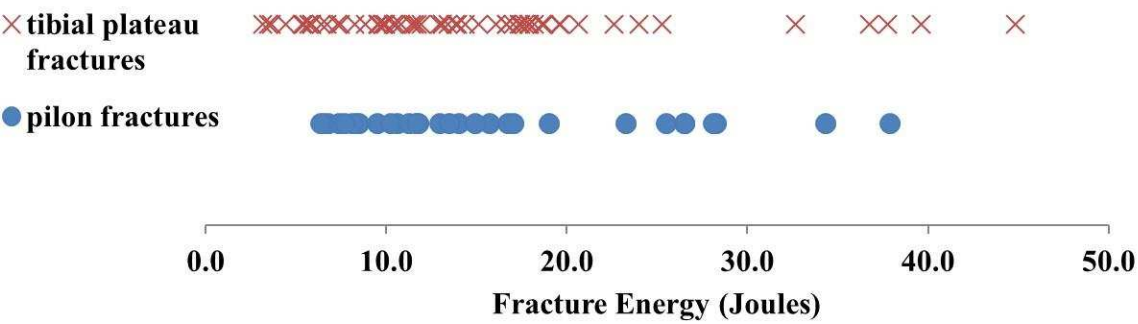
**METHODS:** Fifty-nine tibial plateau fractures (OTA 41-B1 to 41-C3) from a multi-institutional study were specifically selected to span an entire spectrum of injury severity. These were compared with 31 tibial pilon fractures (43-B1 to 43-C3) selected in a similar manner. Fracture energy was calculated using a previously validated CT-based image analysis technique. This was accomplished using specialized software, which identifies all fracture fragments on CT imaging and calculates the amount of free bone surface area generated by the fracture. This surface area and a CT-based metric of bone density are incorporated into an algorithm to calculate fracture energy. Fracture energy values computed for the plateau fractures were compared to those of pilon fractures.

**RESULTS:** The range of fracture energies for tibial plateau fractures was 3.1 J to 44.9 J (Figure 1). The range of fracture energies for pilon fractures was 6.4 J to 37.9 J. The relative distributions of fracture energies within the spectrum for each fracture type were similar.

**CONCLUSIONS:** There were no discernible differences in fracture energy range between the two fracture types, refuting our hypothesis. Similar injury mechanisms typically lead to these two fractures, and previous studies show substantially lower incidences of PTOA resulting from tibial plateau fractures compared to pilon fractures. The findings in this study showing similar energy absorption profiles suggest that the tibial plateau may be more tolerant of impact injury compared to the distal tibia. Additionally, differences in clinical outcomes between the two fracture types are likely not attributable to differences in the fracture energy. PTOA represents an organ-level injury response that is complex and likely joint-specific. Impact tolerance of the proximal tibia may be better explained by differences in cartilage thickness, the inflammatory response after injury, mechanics of joint load distribution, or a variety of other factors. Research reported in this abstract was supported by the National Institute of Arthritis and Musculoskeletal and Skin Diseases of the National Institutes of Health under award number

R21AR061808. The research was also aided by a grant from the Foundation for Orthopaedic Trauma (FOT).

**Figure 1:** Tibial plateau and pilon fracture energy value distributions over a full spectrum of injury severity



**POSTER NO. P511**

**CT-Based Metric of Tibial Plateau Fracture Energy Corresponds Well to Clinician Assessment of Fracture Severity**

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**INTRODUCTION:** Outcomes of intraarticular fractures are influenced both by acute mechanical damage and by residual chronic changes in joint loading. The extent of damage sustained in the acute setting reflects the energy absorbed in creation of the fracture; therefore, fracture energy can be expected to substantially influence clinical outcomes. Previous investigations have demonstrated that objective CT-based quantification of fracture energy in pilon fractures correlates with surgeon assessment of injury severity and two-year radiographic outcomes. It is not clear whether these findings can be extrapolated to other articular fracture types. In this work, we explored whether energy measurement could be used to stratify the severity of tibial plateau fractures. Specifically, we hypothesized that a CT-based measure of fracture energy corresponds to subjective surgeon assessment of fracture severity. We tested the hypothesis by comparing surgeon rank ordering of fracture severity for a series of tibial plateau fractures with CT-based measurements of fracture energy.

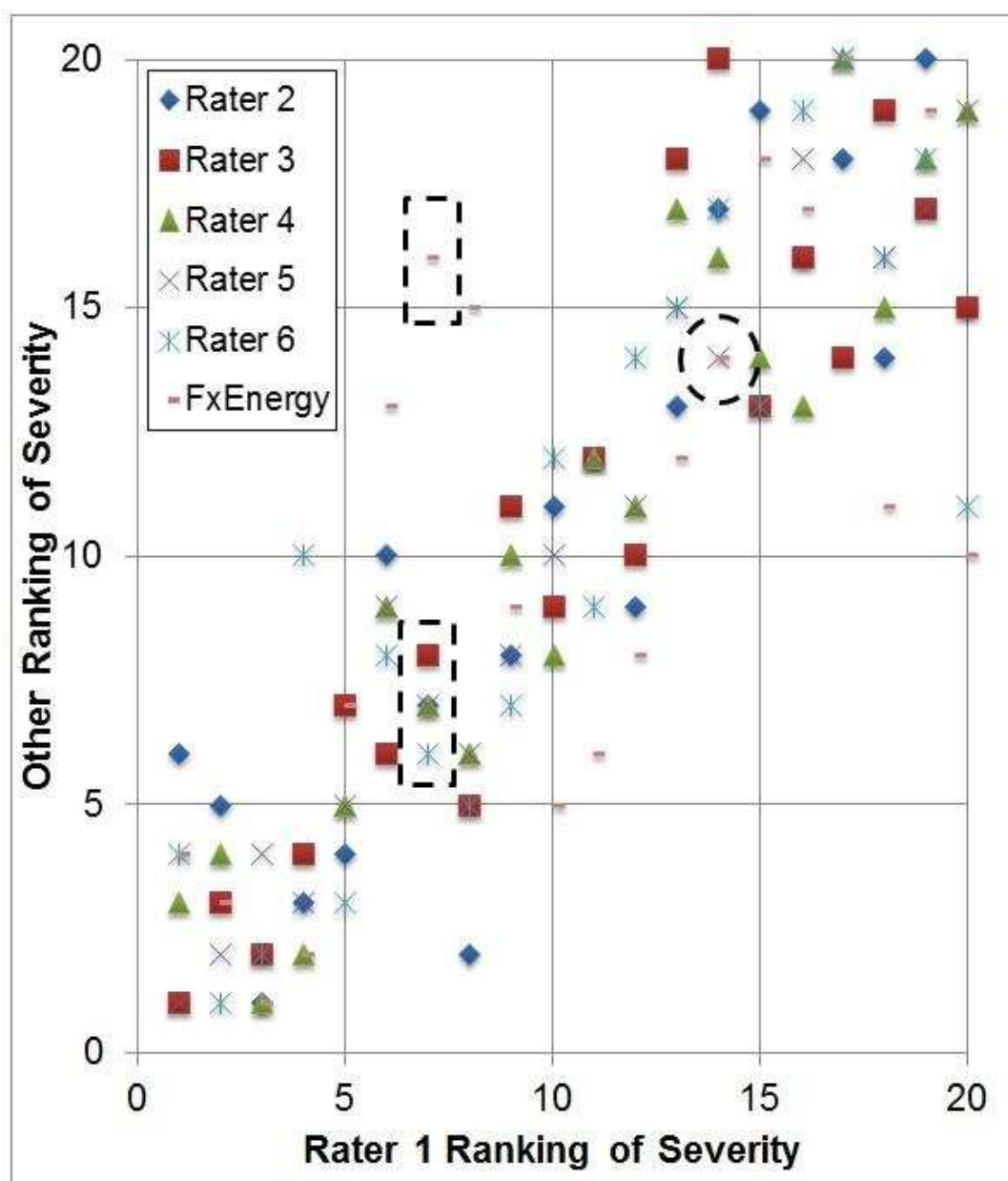
**METHODS:** Twenty fractures were selected from a series of 50 tibial plateau fractures to span a full spectrum of severity. Fracture classification ranged from OTA 41-B1 to 41-C3. Six fellowship-trained orthopaedic trauma surgeons independently rank-ordered the fractures in order of severity using AP and lateral knee radiographs. The raters were instructed to rank the cases in order of least to most severely injured. Subjectively, they used the number and size of fragments, fracture displacement, portion of articular surface involved, and any other features they felt were clinically important. Previously validated, CT-based image analysis software was used to quantify fracture energy based on the amount of bone surface area liberated by the fracture and bone density. The agreement between fracture severity assessments made by the surgeons and the ranking by fracture energy measurement was tested by computing their concordance. A pair of cases' injury severity rankings was deemed concordant if the case with the higher ranking of injury severity for one rater also had the higher ranking for a second rater. Simply put, the rate of concordance is the number of concordant pairs divided by the total number of possible pairings.

**RESULTS:** Concordance between the six orthopaedic surgeons ranged from 82% to 93%. Concordance between surgeon severity ranking and fracture energy ranged from 73% to 78%. See Figure 1.

**CONCLUSIONS:** There is a high level of agreement between surgeon assessment of tibial plateau fracture severity, and CT-based measurement of fracture energy. In addition, agreement among six surgeons with extensive clinical experience judging injury severity was

excellent. Taken together, these results confirm that a CT-based method of calculating fracture energy accurately portrays fracture severity as judged clinically for tibial plateau fractures and provides an objective way to quantify injury severity. Research reported in this abstract was supported by the National Institute of Arthritis and Musculoskeletal and Skin Diseases of the National Institutes of Health under award number R21AR061808. The research was also aided by a grant from the Foundation for Orthopaedic Trauma (FOT).

**Figure 1: Representative rank-ordering of fracture severity by six orthopaedic trauma surgeons and by fracture energy.** The y-axis represents severity ranking as assigned by raters 2-6 and according to the calculated fracture energy. The x-axis represents the rank ordering of rater 1. As an example, there was high agreement between rater 1 and raters 2 – 6 at rater-1 injury number 7, but this fracture's rank according to fracture energy calculation was much higher (black dashed boxes). At rater-1 injury number 14, the rank according to fracture energy was the same as the rank assigned by raters 1 and 5 (dashed circle).



# Quantifying tibial plateau fracture severity: fracture energy agrees with clinical rank ordering

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**Disclosures:** None

**INTRODUCTION:** Outcomes of intraarticular fractures are influenced both by acute mechanical damage and by residual chronic changes in joint loading. The amount of energy dissipated in the creation of a fracture (i.e., the fracture energy) is a physical manifestation of the fracture severity, and it significantly influences outcomes; fracture energy in pilon fractures correlates with surgeon assessment of injury severity and two-year radiographic outcomes [1]. It is not clear whether these findings can be extrapolated to other articular fracture types. In this work, we explored whether this technique of objective fracture energy measurement could also be used to stratify the severity of tibial plateau fractures in a manner that would agree with expert opinions of fracture severity. We hypothesized that an objective CT-based measure of fracture energy would correspond to subjective surgeon assessment of fracture severity.

**METHODS:** A fellowship-trained orthopaedic trauma surgeon selected 20 cases from a series of 50 consecutive tibial plateau fractures to span a full spectrum of fracture severity and to avoid having multiple fractures cluster around a common level of severity. Fracture classifications included OTA 41-B3 and 41-C3. Patients sustaining the fractures ranged in age from 18 to 70-years-old. There were 12 males and 8 females. Our Institutional Review Board approved use of the patient data. Six fellowship-trained orthopaedic trauma surgeons from four separate institutions independently rank-ordered the fractures in order of severity based upon the appearance of the fractures in AP and lateral knee radiographs. The raters were instructed to rank the cases in order of least to most severely injured. A previously validated CT-based image analysis approach was used to quantify the fracture energy based upon measurement of the fracture-liberated surface area and accounting for bone density (Figure 2) [1,2,3]. The agreement between fracture severity assessments made by the surgeons and the ranking by fracture energy measurement was tested by computing their concordance, a statistical measure that estimates the probability that any two cases would be ranked with the same ordering by two different raters or methods. A pair of cases' injury severity rankings was deemed concordant if the case with the higher ranking of injury severity for one rater also had the higher ranking for a second rater, and the concordance was calculated as the number of concordant pairs divided by the total number of possible pairings.

**RESULTS:** Fracture energies ranged from 5.46 J to 36.73 J. There was a high level of agreement between the six experienced surgeons in their assessments of tibial plateau fracture severity (Figure 1), with concordance between the six ranging from 82% to 93% (mean of 85%). The concordance between surgeon severity rankings and the fracture energy severity ranking were slightly less high, ranging from 73% to 78% (mean of 74%). Despite the good overall agreement observed between surgeon assessments of fracture severity and the fracture energy metric, there were some notable exceptions.

**DISCUSSION:** The purpose of this study was to determine whether a CT-based fracture energy metric could provide an objective, quantifiable measure of tibial plateau fracture severity by comparing it to the current gold standard, subjective expert surgeon opinion. We found a high level of agreement (85%) regarding fracture severity among the six orthopaedic trauma subspecialists. The level of agreement between surgeon assessments of fracture severity and fracture energy was not as high (74%), but still much better than chance concordance (50%). These results demonstrate that fracture energy reasonably captures expert opinion regarding the relative fracture severity over a full spectrum of tibial plateau fractures.

**SIGNIFICANCE:** This result provides support for further utilization of an objective CT-based method for determining injury severity.

**REFERENCES:** (1) Thomas TP, et al. *J Orthop Trauma* 24:764-8, 2010. (2) Beardsley CL, et al. *J Biomech* 35:331-8, 2002. (3) Anderson DD, et al. *J Orthop Res* 26:1046-52, 2008.

**ACKNOWLEDGEMENTS:** The research reported in this abstract was supported by the National Institute of Arthritis and Musculoskeletal and Skin Diseases of the National Institutes of Health under award numbers P50 AR055533 and R21 AR061808, as well as by a grant from the Foundation for Orthopaedic Trauma.

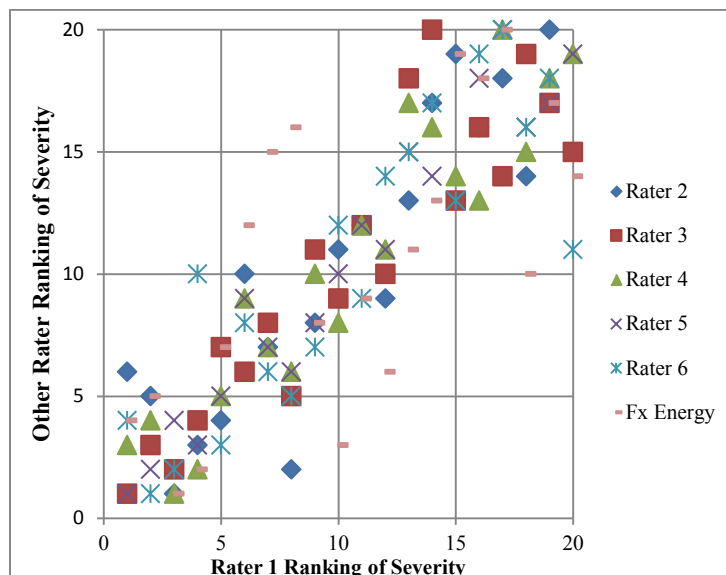


Figure 1: Representative rank-ordering of fracture severity by six orthopaedic trauma surgeons and by fracture energy.

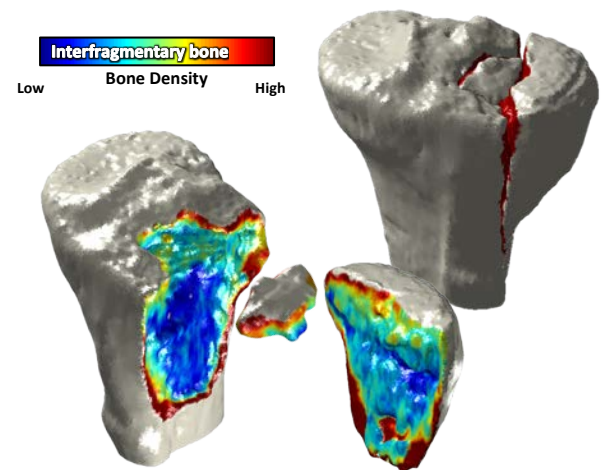


Figure 2: Interfragmentary surface classification for a Schatzker II fracture with a fracture energy of 8.7 J

# Objective fracture energy assessment of tibial plateau fractures loosely corresponds to Schatzker classification

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**INTRODUCTION:** The Schatzker system for classifying tibial plateau fractures was developed as a method for identifying groups of fractures with distinct pathomechanical and etiological factors [1]. Its utility in guiding treatment and predicting outcomes is well established [2], but its accuracy in stratifying the severity of a tibial plateau fracture has never been assessed. The Schatzker system is subjective, and it suffers from poor inter-observer reliability (kappa values from 0.38 to 0.68) [3]. For these reasons, an objective CT-based fracture severity metric has been adapted to assess the energy involved in the fracture creation mechanism [4]. The present study aimed to compare the Schatzker classification of tibial plateau fractures with this objective fracture energy metric to determine how well the classification system captures the energy required to produce a fracture.

**METHODS:** A series of forty patients with tibial plateau fractures, ranging from Schatzker I to VI, were consented for this study. Pre-operative CT scans were used to assess injury severity. A CT-based image analysis methodology was utilized to objectively determine fracture energy based upon the amount of bone surface area liberated by the fracture and accounting for differences in bone density [4,5,6]. Figure 2 demonstrates both the identification of the interfragmentary bone surfaces and the bone density variation. The agreement between the objective fracture energy metric and the Schatzker classification was assessed based upon the concordance in the data. A pair of cases was deemed concordant if the case with the higher fracture energy also had a higher Schatzker classification, and the concordance metric was calculated as the number of concordant pairs divided by the total number of possible pairings.

**RESULTS:** The average fracture energy monotonically increased with increasing Schatzker classification (Figure 1), indicating general agreement between the fracture patterns defined by Schatzker and the energy required to produce such fractures. However, the fracture energies varied, in some instances considerably, within the Schatzker classes. The concordance between the Schatzker classification and the objective fracture energy metric was 70.6%.

**DISCUSSION:** Fractures of the medial tibial plateau (Schatzker IV and V) are generally considered to be more severe, with poorer outcomes when compared to lateral (Schatzker I and II) fractures. The present data suggest that the fracture energy may partly explain these differences in outcomes. Additionally, each Schatzker class included a range of energies, with a large degree of overlap between all categories. High-energy fractures in lower classes may also explain outliers in previous data sets that have relied on Schatzker classification as a surrogate for injury severity.

**SIGNIFICANCE:** The findings of this study suggest that the Schatzker classification is partially representative of the energy that created the fracture but does not capture the range of injury severities within each category. A CT-based fracture energy metric combined with the Schatzker classification may offer advantages of both the anatomic characterization of injury location and an objective assessment of the energy of injury.

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**ACKNOWLEDGEMENTS:** The research reported in this abstract was supported by the National Institute of Arthritis and Musculoskeletal and Skin Diseases of the National Institutes of Health under award numbers P50 AR055533 and R21 AR061808, as well as by a grant from the Foundation for Orthopaedic Trauma.

Figure 1: Schatzker Classification vs Fracture Energy with averages by classification (indicated by red boxes).

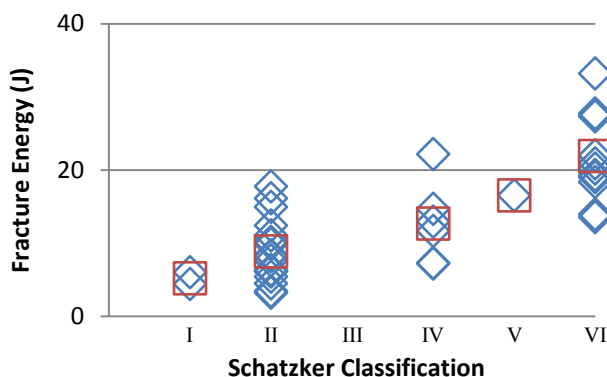
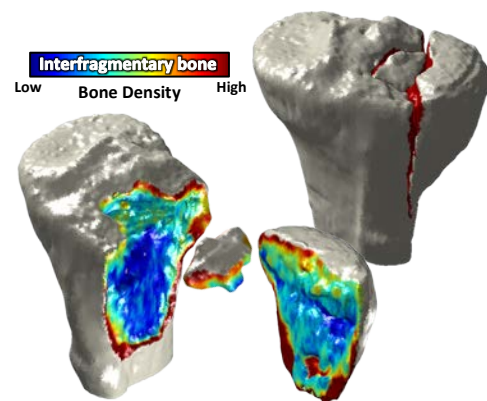


Figure 2: Interfragmentary surface classification for a Schatzker II fracture with a fracture energy of 8.7 J



# Relating Fracture Severity to Post-Traumatic Osteoarthritis Risk after Intra-Articular Calcaneal Fractures

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**Disclosures:** K. Rao: None. K. Dibbern: None. P. Phisitkul: None. J. Marsh: None. D.D. Anderson: None.

**INTRODUCTION:** Patients with high-energy intra-articular fractures (IAFs) face a poor prognosis and a significant risk of developing disabling post-traumatic osteoarthritis (PTOA). Objective CT-based measures of fracture energy have been used to link fracture severity to PTOA risk following IAFs of the distal tibia [1-3], but have never been applied to the calcaneus. The Sanders classification is used as a prognostic marker for long-term clinical outcomes [4] but has not been correlated with fracture energy. The purpose of this study was to establish the relationships between the Sanders classification, fracture energy, the quality of the surgical reduction, and PTOA development in patients with intra-articular calcaneal fractures.

**METHODS:** Eighteen patients with nineteen intra-articular calcaneal fractures were consented for this IRB approved study. The patients were selected as a sample of convenience from a series of 120 cases that have been identified and are being followed. All patients were treated with percutaneous reduction and screw fixation. Standard of care pre-op CT scans were used to classify the fractures according to the Sanders classification and to assess their severity. The Sanders classification for calcaneal fractures is based on coronal and axial CT scan sections, where type I are non-displaced IAFs; type II are two-part or split fractures of the posterior facet; type III are three-part fractures of the posterior facet (with two fracture lines and a centrally depressed fragment); and type IV are comminuted fractures [5]. Fracture severity was quantified by fracture energy, which is proportional to the fracture-liberated surface area of bone [1, 6-7]. A CT-based image analysis methodology was used to identify and measure the inter-fragmentary surface area (Figure 1). The liberated surface area was multiplied by the energy release rate, scaled by CT intensities to account for variation in bone density, to calculate the fracture energy [2,7]. Three experts independently measured the maximum articular step-off, a measure of the quality of surgical reduction, visualized on a post-op CT. PTOA development was graded using the Kellgren-Lawrence (KL) scale for all patients with a follow up time > 18 months. Because the measures to be compared mix ordinal and continuous values, agreement was assessed using concordance—the probability that the fracture energies correctly discriminate between pairs of Sanders classification and/or KL scores.

**RESULTS:** The nineteen calcaneal fractures analyzed for fracture severity ranged from Sanders class II to IV. Their fracture energies ranged from 12.3 to 24.5 J (mean  $\pm$  standard deviation =  $18.0 \pm 2.9$  J). A concordance of 0.75 was observed between Sanders classification and fracture energy. Ten patients with eleven intra-articular fractures were assessed for PTOA development, based on a follow up time > 18 months. For those ten patients, the most recent follow-up radiographs available were obtained between 20 and 74 months post-injury. There was a complex relationship observed between fracture energy, Sanders classification, articular step-off, and KL grade. When cases were segregated based on the articular reduction obtained being less than 2 mm, a pattern of increasing PTOA risk with increasing fracture energy emerged (Figure 2). There was no such relationship observed between Sanders classification and KL grade.

**DISCUSSION:** The results suggest that fracture severity is more predictive of PTOA risk than is the Sanders fracture classification. The residual articular step-off is a likely confounder influencing PTOA risk when evaluating fracture energy vs KL grade. Cases with an articular step-off < 2 mm demonstrated a positive association between fracture energy and risk of PTOA. Due to a small sample size, statistical significance could not be conclusively established.

**SIGNIFICANCE:** These data suggest that higher initial injury severity as assessed by an objective metric could predict an increased risk of PTOA. This has implications for evaluation and treatment of calcaneal fractures with the aim of forestalling PTOA.

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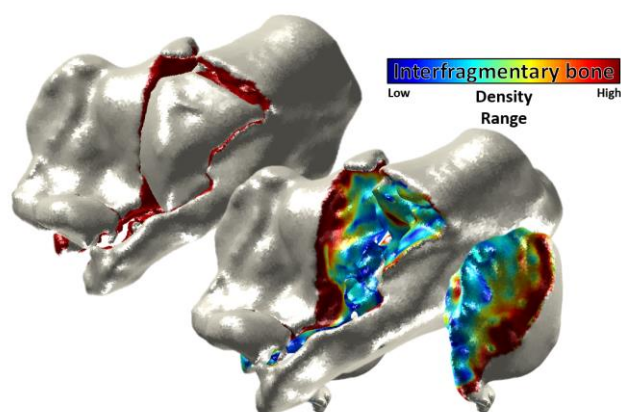


**Figure 1.** 3D model of a Sanders class III intra-articular calcaneal fracture. Left: inter-fragmentary surface area (red). Right: inter-fragmentary bone with energy density range.

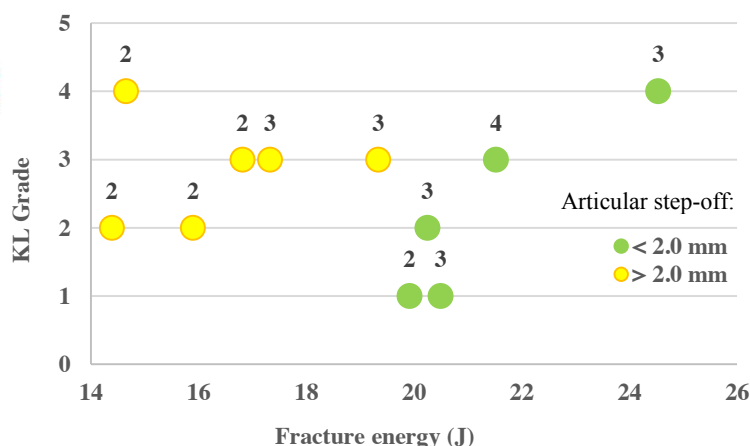


**Figure 2.** Fracture energy vs KL Grade. Number above data points indicates Sanders classification.

# Elevated Contact Stress after Surgical Reduction of Acetabular Fractures Correlates with Progression to Post-Traumatic Osteoarthritis

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## INTRODUCTION

Residual incongruity following surgical reduction of acetabular fractures is associated with post-traumatic osteoarthritis (PTOA) [1]. Malreduction greater than 2mm is considered significant. Despite advances in reduction and fixation strategies over the past two decades, there remains a significant prevalence of PTOA in patients that suffer from acetabular fractures [1]. The strong association of PTOA to subtle fracture malreduction suggests that the joint degeneration has a mechanical origin. Elevated joint contact stress, as is often found with fracture malreduction, has previously been demonstrated to predict PTOA development in the distal tibia [2]. Despite this strong mechanical association of elevated contact stress with PTOA progression, this relationship has not yet been investigated in patients after acetabular fractures. The goal of this study was to determine if contact stress elevation following surgical fracture reduction is related to PTOA incidence in patients with acetabular fractures.

## METHODS

In this study, a series of 11 patients with surgically reduced acetabular fractures were retrospectively studied. These patients were the first to be analyzed from a larger series of patients being studied. The average patient age was 43.3 years (range: 27-69 years). Patient-specific geometries of hip joints were segmented from post-operative CT-scans and utilized to perform computational contact stress analysis through a previously validated discrete element analysis (DEA) methodology [3]. Contact stresses were computed at heel-strike, mid-stance, and toe-off stages of the gait cycle to determine the maximum contact stress at critical points in gait. The overall average maximum contact stress for each case was determined by taking the mean of these

maximum contact stress values. Patient outcomes were evaluated by the Kellgren-Lawrence arthrosis grade (KL grade) from follow-up weight-bearing radiographs obtained at a minimum follow-up of two years (range: 27-68 months).

## RESULTS AND DISCUSSION

All fractures had at least 2mm of malreduction on post-operative CT scans. The average maximum acetabular contact stresses ranged from 5.2 to 21.7 MPa. KL grades ranged from 0 (no PTOA) to 4 (significant PTOA). There was a strong positive correspondence between maximum contact stress and KL grade (Figure 1). The three patients with the lowest maximum contact stress (range: 5.2 to 8.4 MPa) had the lowest KL grade of 0, while the 4 cases with the highest maximum contact stress (19.5 to 21.7 MPa) had a KL grade of 4.

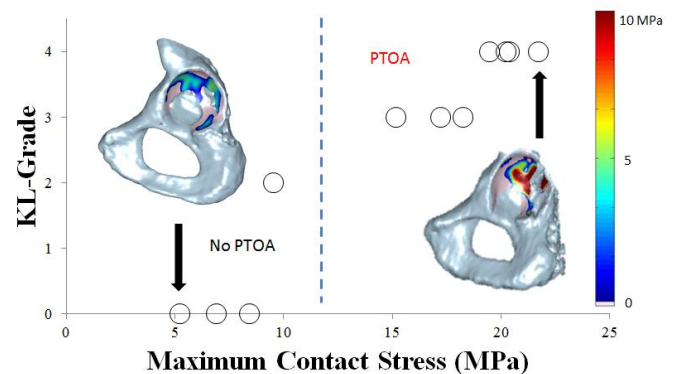


**Figure 1.** KL grade vs. maximum contact stress at greater than two year follow-up.

Of the 11 acetabular fracture patients analyzed, 7 had developed PTOA of the hip (KL grade > 2) and an average maximum contact stress of greater than 10 MPa. The other four patients did not develop PTOA (KL grade ≤ 2), further demonstrating the strong relationship between contact stress and PTOA. Five patients, with maximum contact stresses ranging

from 15.1 to 21.7 MPa, had been converted to a total hip arthroplasty. Table 1, below, shows the outcome for each patient as well as the average maximum contact stress computed in each hip.

## CONCLUSIONS

This series of patients, the first to be analyzed from a larger series, demonstrate a strong relationship between post-operative elevated contact stresses and progression to PTOA in patients that undergo surgical reduction of acetabular fractures. These results support clinical observations that malreduction of acetabular fractures leads to a high rate of joint failure. Our series of patients demonstrated that joint contact stress exceeding approximately 10 MPa resulted uniformly in PTOA. This is comparable to thresholds for joint contact stresses that predictably lead to PTOA in articular fractures of other lower extremity joints [2].

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## ACKNOWLEDGMENTS

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**Table 1:** Average maximum contact stresses for each stage of gait cycle recorded for each case and additional case information used for data.

| Average Maximum Contact Stress | Total Hip Replacement | PTOA development | KL grade |
|--------------------------------|-----------------------|------------------|----------|
| 5.19                           | No                    | No               | 0        |
| 6.91                           | No                    | No               | 0        |
| 8.42                           | No                    | No               | 0        |
| 9.53                           | No                    | No               | 2        |
| 15.14                          | Yes                   | Yes              | 3        |
| 17.22                          | Yes                   | Yes              | 3        |
| 18.24                          | No                    | Yes              | 3        |
| 19.48                          | No                    | Yes              | 4        |
| 20.25                          | Yes                   | Yes              | 4        |
| 20.39                          | Yes                   | Yes              | 4        |
| 21.73                          | Yes                   | Yes              | 4        |

# Clinical Fractures of the Tibial Plateau Involve Similar Energies as the Tibial Pilon

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## INTRODUCTION

Post-traumatic osteoarthritis (PTOA) frequently occurs secondary to joint injuries, with articular fractures in the lower extremity particularly at risk. Despite similar injury mechanisms, incidence of PTOA is much higher in patients with fractures of the tibial pilon (74%) than those with fractures of the tibial plateau (22-44%).[1-2] The reasons for this difference are not well understood.[3] Surgeons have adopted fracture severity assessment methods to aid in treatment decision-making. However, conventional systems for classifying fractures are highly subjective, have poor reproducibility, and cannot reliably predict PTOA.[4]

Fracture severity can be objectively assessed using the amount of energy absorbed in fracturing a bone (i.e. fracture energy). In tibial pilon fractures, fracture energy is significantly correlated with PTOA incidence.[5] This study used an objective CT-based methodology for measuring fracture energy to explore the hypothesis that fracture energies are higher in pilon fractures compared to plateau fractures. The relationship between fracture energy and present clinical fracture classification systems was also explored to determine how well classifications reflect severity.

## METHODS

Fellowship-trained orthopaedic trauma surgeons enrolled 75 patients with tibial plateau fractures and 52 patients with tibial plafond fractures. Fracture energies were calculated using a previously validated, objective, CT-based image analysis methodology (Figure 1). [5]

The fractures were also characterized according to the AO/OTA fracture classification system by three fellowship-trained orthopaedic traumatologists. The AO/OTA classification seeks to categorize fractures based upon morphological characteristics in order

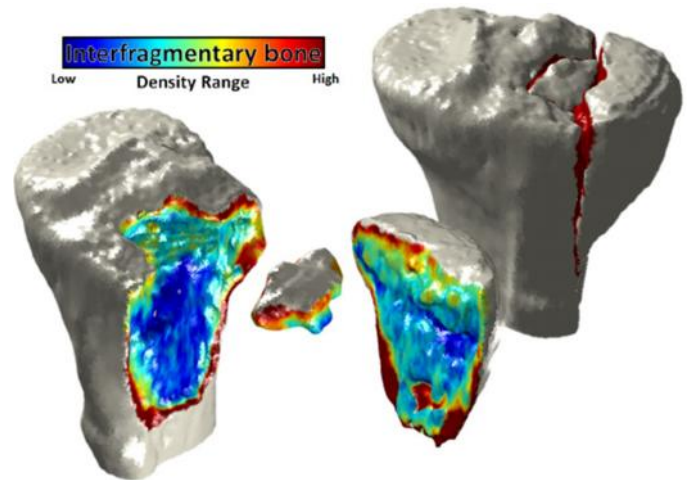


**Figure 1.** The surface area generated from the fracture (fracture-liberated surface area) and the bone densities across that surface were used to calculate fracture energy.

of increasing complexity and severity, where severity “implies anticipated difficulties of treatment, the likely complications, and the prognosis.” [6]

## RESULTS

The range of fracture energies measured for tibial plateau fractures was 3.2 to 33.2 (13.3±6.8) Joules and 3.6 to 32.2 (14.9±7.1) Joules(J) for tibial pilon fractures. AO/OTA fracture classifications ranged from 41-B1 to 41-C3 and the pilon fractures ranged from 43-B1 to 43-C3. The distribution of energies within the spectrum for each fracture class was similar. The average fracture energies for the most part increased with increasing AO/OTA classification indicating a loose general agreement on severity (Figure 2).

## DISCUSSION

There were no discernible differences in fracture energy range or distribution between plateau and pilon fracture types, refuting our original hypothesis. Similar injury mechanisms typically lead to these two fractures, and previous studies

show a substantially lower incidence of PTOA resulting from plateau fractures compared to pilon fractures. Impact tolerance in the proximal tibia may be better explained by differences in morphology/anatomy, cartilage thickness, joint mechanics, or a variety of other factors.[7,8]

The larger range of fracture energies seen in higher classes of fracture energies may reflect the fact that more complex and variable injuries make up these classes. However, the higher class fracture patterns were not necessarily more severe (i.e., did not always have higher fracture energies). This suggests that fracture classifications are less reflective of severity for more complex fracture patterns. A surprisingly wide range of fracture energy was seen for the fracture classifications assessed. This suggests that these classifications are not a reliable surrogate for fracture severity. Combining fracture classification, which captures the morphologic characteristics of the fracture, with objective measurement of fracture energy would provide a more complete assessment of articular fractures.

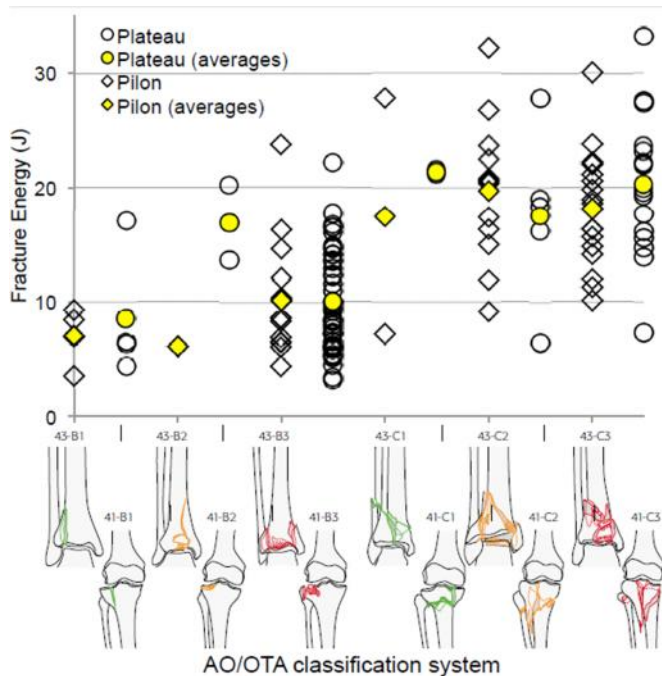


**Figure 2.** Range of fracture energies as they vary over the different AO/OTA classes for the tibial plateau and pilon fractures.

## CONCLUSIONS

Historically, studies comparing different groups of fractures have used AO/OTA fracture classification to show that the groups had similar fracture characteristics and severity. Perhaps the most useful conclusion from these data is that prior studies failing to demonstrate group equivalence simply by showing no statistical difference in fracture classification type are missing critical information about underlying differences in fracture severity. Assigning "high energy" and "low energy" based on injury mechanism and fracture pattern is largely subjective and fails to sufficiently stratify severity. The data presented in this study provide strong evidence of the utility that fracture energy has in the context of clinical research.

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## **Post-Traumatic OA Risk Relative to Intra-Articular Calcaneal Fracture Severity**

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**PURPOSE:** Patients with high-energy intra-articular fractures (IAFs) face a significant risk of post-traumatic osteoarthritis (PTOA). Objective CT-based measures of fracture energy have been used to link fracture severity to PTOA risk following IAFs of the distal tibia [1-3] but not the calcaneus. The Sanders classification is used as a prognostic marker for long-term clinical outcomes [4] but has not been correlated with fracture energy. The purpose of this study was for the first time to objectively measure fracture energy in a series of calcaneal fractures and to establish the relationships between it and the Sanders classification, the quality of the surgical reduction, and clinical outcome in patients with intra-articular calcaneal fractures.

**METHODS:** Eighteen patients with nineteen IAFs of the calcaneus were consented for this IRB-approved study; they are the first to be analyzed from a series of 120 cases treated with percutaneous reduction and screw fixation that have been identified and are being followed. Pre-op CT scans were used to classify fractures according to Sanders et al. [5] and to assess their severity. Fracture severity was quantified by computing fracture energy using a CT-based image analysis methodology. [2] Three experts independently measured the maximum articular step-off from post-op CT. PTOA development was graded using the Kellgren-Lawrence (KL) scale and outcomes were assessed with VAS pain scores for patients with >18 month follow up. Because the measures to be compared mix ordinal and continuous values, agreement was assessed using concordance – the probability that the fracture energies correctly discriminate between pairs of Sanders classification and/or KL scores.

**RESULTS:** The nineteen calcaneal fractures analyzed for fracture severity ranged from Sanders class II to IV. Their fracture energies ranged from 12.3 to 24.5 J. A concordance of 0.75 was observed between Sanders classification and fracture energy. Ten patients with eleven intra-articular fractures were assessed for PTOA development, based on a follow up time > 18 months (range: 20 to 74 months) post-injury. There was a complex relationship observed between fracture energy, Sanders classification, articular step-off, and KL grade. Interestingly, for those cases having an articular step-off < 2 mm, PTOA risk increased with fracture energy (Figure 1). There was no such relationship observed between Sanders classification and KL grade.

**CONCLUSION:** The results suggest that fracture severity is more predictive of PTOA risk than is the Sanders classification. The residual articular step-off is a likely confounder influencing PTOA risk when evaluating fracture energy vs KL grade. Due to a small sample size, statistical significance could not yet be conclusively established. These data suggest that higher initial injury severity as assessed by an objective metric could predict an increased risk of PTOA. This has implications for evaluation and treatment of calcaneal fractures with the aim of forestalling PTOA.

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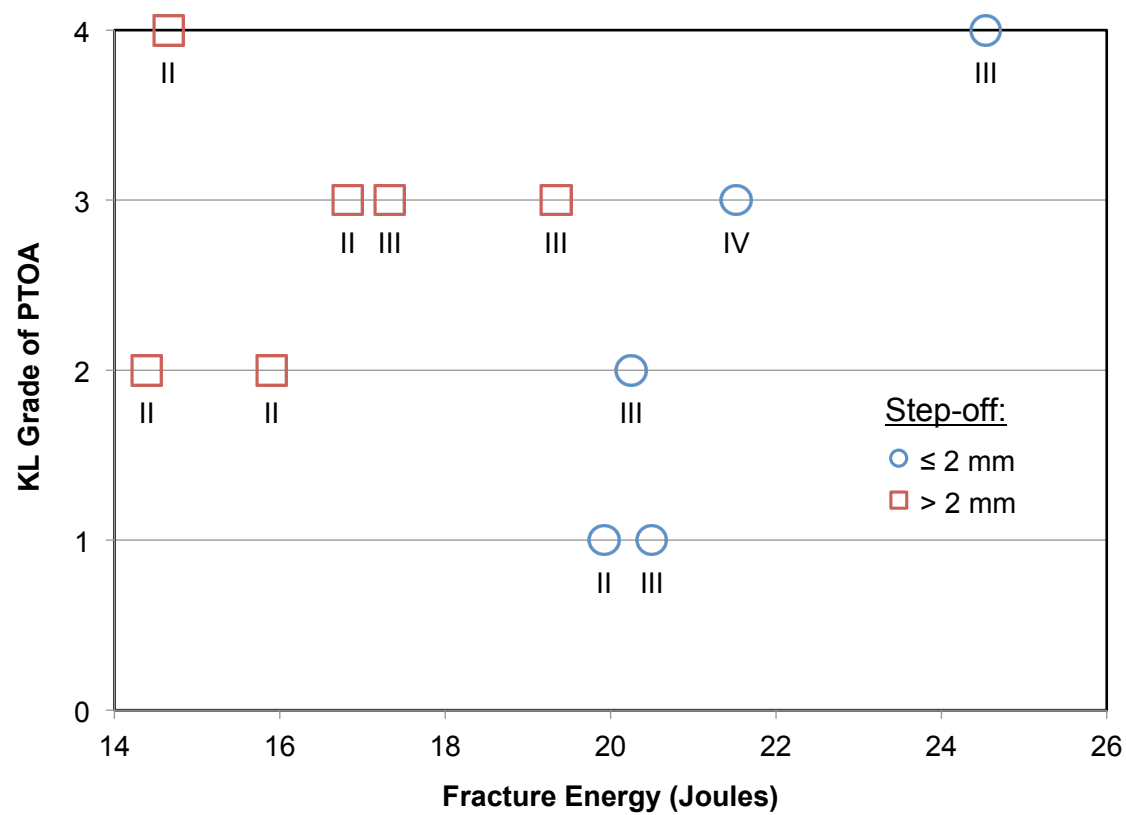


**Figure 1.** Fracture energy vs KL Grade. Labels below data points indicate the Sanders fracture classification.

# A universally applicable, objective CT-based method for quantifying articular fracture severity

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**INTRODUCTION:** The assessment of injury severity is a critical step in the treatment of articular fractures. Severity assessments are used to inform clinical and surgical decision making through anticipation of patient outcomes. These assessments generally involve interpretation of radiographs or CT image data to characterize aspects of the fractures that predispose to poor prognoses. In recognition of the poor reliability of existing clinical severity assessments, new objective severity metrics have been developed that are firmly rooted in mechanics and provide capable alternatives for use in research, where reliable data are paramount. One of these metrics, fracture energy, has previously been relegated to use in a single joint. In an effort to expand the clinical utility of fracture energy as an objective metric of severity, we have developed new methods to implement fracture energy as a universal tool in any fracture with pre-operatively available CT-scans.

**METHODS:** An existing, objective, CT-based method for determining the energy expended in a bone fracture was extended to enable its 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 a 3D model of the fracture. Surfaces are then smoothed in Geomagic Design X (3DS Systems, Rock Hill, SC) to remove voxelation effects 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 which had previously been assessed using the existing methods.

**RESULTS:** The fracture energies computed using the new assessment methodology were compared to those computed using the prior method for validation purposes. Twenty tibial pilon fracture cases previously analyzed were evaluated using the new methodology. A Bland-Altman plot comparing the results is shown in Figure 1. There was strong agreement between the previous fracture energy evaluation method and the expanded methodology with all but one case lying within the confidence interval. On average, there was a bias that the prior methodology measured around 1.5J higher than the present method; based upon these cases, the data suggest that 95% of measurements with the new methodology will be within 3-5J of those made using the prior methodology.

**DISCUSSION:** Fracture energy is a proven metric capable of objectively analyzing fracture severity over a continuous spectrum of severity. Previous methodologies were limited by their requirement of intact contralateral scans and joint specific parameters. The new methodology has more flexibility as it only requires a CT-scan containing the fractured region and can be readily retrained to classify fractured areas in any joint. The simple articular comminution metric is also readily applicable to any articular fracture (see Figure 2 for the evaluation of a tibial plateau fracture). The articular fracture edges are readily identified in any joint and have physiological meaning, as chondrocyte death is known to be elevated along fracture edges.

**SIGNIFICANCE:** The methods for assessing fracture energy described are highly useful for stratifying severity over a continuous range. It has the potential to be an important tool for both clinical and research applications within orthopaedics.

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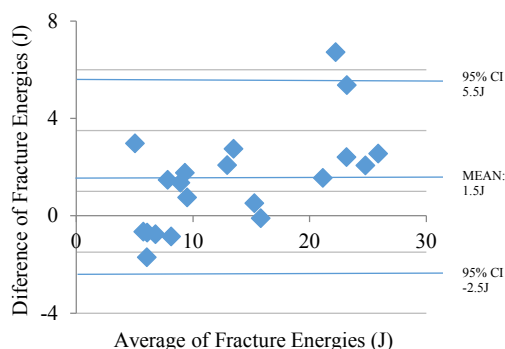


**Figure 1.** Bland-Altman plot comparing fracture energies obtained from the original and the newly expanded methodologies.

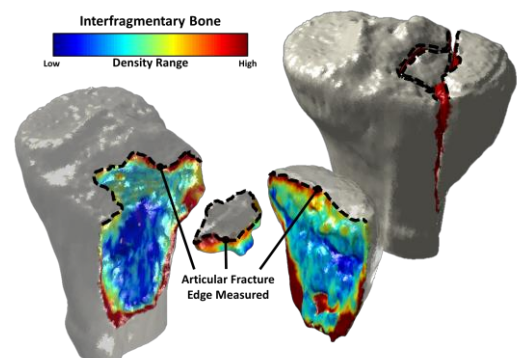


**Figure 2.** Fracture-liberated surface area and bone densities shown across an exploded view of a tibial plateau fracture. The dashed lines indicate where the articular comminution measure is obtained from.