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

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Abstract

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

Design: Retrospective review and fracture severity analysis

Setting: The University of Iowa Hospitals and Clinics is a level 1 trauma center affiliated with the University of Iowa in Iowa City, Iowa.

Patients/Participants: Thirty-six patients with 48 DIACFs were selected from 153 patients previously treated. All patients 18 years old that had available electronic pre-op and post-op CT scans, good quality post-op and follow up radiographs, and a follow up 18 months were selected for study.

Intervention: Fractures were treated with percutaneous reduction, using multiple small stab incisions and fluoroscopy to guide manipulation of articular fragments using cork screws or Steinmann pins, with subsequent fixation using 3.5- and 4.0 mm screws.

Main Outcome Measurements: Pre-op CT scans were used to grade fractures according to the Sanders classification and to quantify fracture severity. Fracture severity was objectively quantified using a CT-based measure of fracture energy. PTOA was assessed on follow up radiographs using the Kellgren-Lawrence scale. Patient outcomes were assessed using the Short Form 36 (SF-36) questionnaire and a visual analogue scale pain score.

Results: Fracture energies for the 48 DIACFs ranged from 14.1 to 26.2 J (19.3 ± 3.1 J) and correlated with Sanders classification ($\rho=0.53$, $p=0.0001$); type I [16.3 ± 0.9 J]; type II [18.0 ± 2.7 J]; type III [20.8 ± 2.8 J]; type IV [22.0 ± 0.7 J]. Fracture energy was higher for fractures in which the subtalar joint developed PTOA (19.5 ± 2.7 J) than for those that did not (18.9 ± 3.3 J), but the difference did not reach statistical significance. Sanders classification predicted PTOA risk

(OR=4.04, 95%CI=1.43–11.39, $p=0.0084$). No relationship was observed between fracture energy and VAS pain scores. A higher fracture energy correlated to lower SF-36 scores.

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

Level of Evidence: Prognostic, level III

INTRODUCTION

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

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

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

METHODS

To assess fracture energy and correlate it with key dependent variables, a convenience sample of patients with DIACF was chosen from a larger series of patients that were identified. Thirty-six patients with 48 DIACFs were selected for study from among 153 patients that had been treated (see Figure, Supplemental Digital Content 1, which shows sample selection for the study). The patients selected were age ≥ 18 years, had available electronic pre-op and post-op CT scans, and good quality post-op and follow up radiographs. Patients age < 18 , extra-articular fractures, patients without pre-op CT scans, and follow up < 18 months were excluded. The patients' charts and radiographs were accessed retrospectively after IRB approval. Demographic data and patient characteristics are shown in Table 1.

Pre-op fracture classification

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

Operative protocol and articular step off

Fractures were treated with percutaneous reduction, using multiple small stab incisions and fluoroscopy to guide manipulation of articular fragments using cork screws or Steinmann pins, with subsequent fixation using 3.5- and 4.0 mm screws.^{7, 8} No mini open incisions or plates were used. All procedures were performed by either a fellowship-trained orthopedic trauma surgeon or a fellowship-trained orthopedic foot and ankle surgeon. Surgical reduction was assessed by measuring the posterior articular surface residual step-off using a semi-automated 3D step-off measurement tool coded in MATLAB (MathWorks, Inc., Natick, MA) software. Three patients with 4 fractures did not have post-op CT scans available to assess articular step off but were still included in the study.

Assessment of fracture severity

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

Assessment of PTOA and clinical outcomes

PTOA was assessed on follow up radiographs using the Kellgren-Lawrence (KL) scale.⁹ The same three clinicians independently assigned a KL grade to the subtalar joint using available post-op AP, lateral, and Broden radiographs of the calcaneus. The radiographs were assessed at follow up times ranging from 19 to 84 months, with a median follow up time of 43

months. Disagreement in evaluation of KL grades was adjudicated by majority vote of all three evaluators. A KL grade 2 met criteria for PTOA.

Patients were clinically evaluated using functional outcome questionnaires scored from chart review. To evaluate clinical health score trends, fracture energy was arbitrarily divided into three categorical energy ranges (“low,” “medium,” and “high”) with the goal of having an approximately equal number of fractures in each category. Two clinical health outcome scores were obtained: the visual analog scale (VAS) for pain, and the Short Form 36 (SF-36) quality of life survey. The SF-36 is a widely used quality of life survey composed of a physical component summary (PCS) and a mental component summary (MCS), with each category scoring from 0–100, and higher scores representing better outcomes.¹⁰

Statistical methods

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

RESULTS

Fracture energy and Sander’s classification as predictors of PTOA

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

Fracture energies showed overlap across different grades of PTOA (see Table, Supplemental Digital Content 2, which shows mean fracture energy and follow up time, along with the number of fractures for each radiographic grade of PTOA). 14/48 fractures had a one-grade discrepancy in independent evaluation of KL grades, and an additional 4/48 fractures had a two-grade discrepancy, before subsequent consensus; 1/48 fractures had a three-grade discrepancy, as assessed by a PGY-3 resident and an orthopedic trauma surgeon (inter-rater reliability coefficient of concordance $\tau = 0.6$, $p=0.0074$). Stratifying these data by the presence of radiographic PTOA (KL 2), the fracture energy was higher for fractures in which the subtalar joint developed PTOA (19.5 ± 2.7 J) than for those fractures in which the

subtalar joint did not (18.9 ± 3.3 J), but the difference did not reach statistical significance (OR = 1.37, 95% CI = 0.53–3.51, $p=0.52$) (Figure 3).

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

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

Sanders classification positively correlated with the risk of developing PTOA (OR = 4.04, 95% CI = 1.43–11.39, $p=0.0084$), and the results were significant even when adjusted for follow-up time between the PTOA and non-PTOA groups (OR=4.60, 95%CI = 1.30–16.28, $p=0.0179$). For Sanders type I fractures, no evidence of PTOA was observed. For type II fractures, an equal number of subtalar joints developed PTOA as did not. A greater percentage (72%) of subtalar joints developed PTOA in Sanders type III and IV fractures (Table 2). Sanders classification did not correlate with the likelihood of subtalar arthrodesis (OR=1.39, 95% CI = 0.48–4.00, $p=0.5399$).

Clinical outcomes and functional scores

VAS pain scores were available for all 36 patients, and SF-36 scores were available for 28 of 36 patients (see Table, Supplemental Digital Content 3, which shows VAS and SF36 scores across fracture energy). Taken across the aggregate fracture energy range, there was a weak negative correlation between fracture energy and VAS pain scores ($\rho = -0.13$, $p=0.3764$). Patient-reported SF-36 PCS were lower for high energy fractures. This result was more pronounced in patients with bilateral fractures ($\rho = -0.76$, $p=0.0018$, $n=14$). There were no significant associations observed between fracture energy and SF-36 MCS, although there was a trend for lower scores with higher energy fractures.

Somewhat unexpectedly, patients who developed PTOA did not report significantly higher VAS pain scores than patients who did not (see Table, Supplemental Digital Content 4, which shows VAS and SF-36 scores with respect to PTOA). However, both SF-36 PCS and MCS were lower among patients who developed PTOA than in those who did not [PCS (PTOA: 34.7, no PTOA: 45.0; $p=0.013$), MCS (PTOA: 47.9, non PTOA: 55.8; $p=0.045$)]. An inverse relationship was observed between Sanders classification and VAS pain scores. Although generally decreasing with higher Sanders classification, SF-36 MCS scores did not differ significantly across Sanders fracture types, while SF-36 PCS scores significantly decreased.

Outcomes by surgical reduction

With respect to the quality of surgical reduction, 25 of 44 fractures (56.8%) measured a step off < 2 mm, and 19 of 44 fractures (43.2%) measured a step-off > 2 mm. No correlation was

observed between fracture energy and articular step-off. A non-significant positive association was observed between articular step-off and KL grades (see Table, Supplemental Digital Content 5, which shows articular step off for fractures by KL grade). Similarly, a positive correlation was observed between Sanders classification and articular step off, but the finding was also not statistically significant.

DISCUSSION

Correlation of fracture energy with Sanders classification

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

Fracture classification systems are often used to provide a clinician-assessed indicator of fracture severity but suffer from poor inter-observer reliability when clinicians' place fracture patterns into categorical classification schemes.^{3,4} This study demonstrated poor inter-observer reliability in classifying DIACFs by the Sanders Classification (concordance $\tau = 0.6$, $p=0.0074$). The Sanders classification is commonly used to assess DIACFs and has been previously found to be prognostic of long-term patient outcomes.^{15–18} We found that fracture energy generally increased with Sanders classification. This is an expected result; Sanders classification is based on the number of fracture lines through the posterior facet. More fracture lines through the posterior facet generally correlates with greater inter-fragmentary surface area, translating into higher energy. There was, however, considerable overlap among classification of fracture types and fracture energy, which may in part be explained by the fact the Sanders classification assesses only the number of intraarticular fracture lines, whereas the fracture energy calculation accounts for extra-articular extension of the fracture which may vary across otherwise similar Sanders grades.

Fracture energy as a predictor of PTOA

In this study, 61% of patients developed radiographic evidence of PTOA, and 22% of patients progressed to subtalar joint fusion, at a median of 36 months post injury. Previous studies have demonstrated that fracture severity metrics applied to tibial pilon fractures strongly correlate with subsequent PTOA.^{1, 2, 4} In this study, this relationship was less evident for DIACFs. While mean energy was higher for fractures in which the subtalar joint progressed to PTOA, there was significant energy overlap with those that did not. The

pathogenesis of PTOA is heterogeneous and may result from persistence of a pathologic process initiated at the time of initial joint trauma or a combination of pathological and inflammatory processes that take place in damaged tissue.¹⁹ Additionally, independent risk factors such as obesity, smoking, age, sex, and activity levels are likely to confound the relationship between fracture energy and PTOA.

The clinical significance of fracture energy is that it (1) provides a truly objective assessment of fracture severity, (2) provides a means to test how well subjective classification schemes reflect fracture severity, (3) can guide surgeon decision making for minimally invasive versus open intervention techniques, and (4) may predict and inform patients of their PTOA risk. Of course, these clinical benefits can only be fully realized once fracture energy can be routinely quantified in practice.

This study also assessed the effect of another important variable, the residual mechanical environment caused by persistent articular step offs. Multiple studies have suggested that fractures with an incongruous reduction (i.e., step off > 2 mm) are associated with early PTOA; however, evidence is less clear on the relationship between poor reduction and worse long-term clinical outcomes.^{11, 19–22} In this study, fracture energy did not correlate with articular step off, but there was a positive association between KL grade and articular step off, as well as between Sanders classification and articular step off; however, these differences were not significant. Articular step off is an important source of expected PTOA, but other factors including cartilage loss at time of surgery, and abnormal alignment of the body leading to uneven wear also influence PTOA risk from the time of surgical intervention to arthritis development.

Correlation to clinical outcomes

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

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

Limitations

KL grading has previously been demonstrated in the literature to be subjective with moderate inter-observer reliability in the subtalar joint.^{23–26} In this study, inter-observer reliability in assessing PTOA on plain radiographs was in the moderate range ($\tau=0.6$). The

lack of CT imaging to assess PTOA was a limitation, and further research assessing PTOA with weight bearing CT scans may more accurately characterize subtalar PTOA. Another limitation was the form in which the VAS pain scores were charted on a 3 point range in patient records (for example, “moderate pain, VAS 4–6”), instead of a true 10 point scale. This may explain the significant overlap in pain scores and limited statistical significance observed with fracture energy.

Sample size was also a limitation. Ideally, a higher fracture energy suggests a more severe fracture pattern (which we observed with the Sanders classification), which in turn should reflect a higher PTOA risk. Possible confounding factors between fracture energy and PTOA risk include anatomical reduction (<2 mm), gender, age, BMI, comorbidities, and a shorter follow up time in the non-PTOA group. Radiographic PTOA was assessed in this study. Defining PTOA from a biological and pain perspective creates additional complexities as the pathogenesis of PTOA is in itself complex, as is how patients interpret and report pain. Sanders classification positively correlated with the risk of developing PTOA, consistent with literature,¹⁸ but did not correlate with risk of subtalar fusion. Weak positive correlations between KL grades and articular step off, as well as between Sanders classification and articular step off were observed, which may have reached statistical significance with a larger sample size.

CONCLUSIONS

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

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1. Superior views of a Sanders type III intra-articular fracture of the calcaneus. From left to right: (A) patient-specific CT slice with overlay of image segmentation of fracture fragments; (B) two fracture lines coursing through the posterior talar articular surface demonstrating a Sanders type III fracture pattern; (C) 3D model of the fracture generated by custom-written MATLAB software; (D) exploded view showing inter-fragmentary bone surfaces and CT-derived densities used to calculate the fracture energy. [A= anterior talar articular facet; M = middle talar articular facet; P = posterior talar articular facet]

Figure 2.

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

Figure 3. Fracture energy (J) vs PTOA development in the subtalar joint for calcaneus fractures. 29 subtalar joints developed radiographic PTOA with an energy of $19.5 \text{ J} \pm 3.3 \text{ J}$. 19 subtalar joints did not show radiographic evidence of PTOA, with a mean energy of $18.9 \text{ J} \pm 2.8 \text{ J}$. $P=0.5314$.

Table 1.**Patient characteristics**

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

BMI: body mass index; KL: Kellgren-Lawrence

Table 2:

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

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

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