Step-off Vs. Contact Stress Following Articular Fracture Reduction: Which Measure Is Better For Predicting PTOA?

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Introduction: Altered joint mechanics following intra-articular fracture is a major contributing factor in the development of post-traumatic osteoarthritis (PTOA), primarily due to increased contact stress exposure from residual joint incongruity. Although a variety of clinical and experimental metrics have been used to quantify joint incongruity, there is still question as to the importance of step-off magnitude in PTOA development [1]. Previously, finite element analysis (FEA) was used to examine the relationship between chronic contact stress over-exposure following tibial plafond fracture and 2-year post-op Kellgren-Lawrence (KL) grade [2, 3]. In a cohort of eleven patients a contact stress over-exposure metric was found that had a 100% concordance with PTOA development (KL grade ≥ 2) and a 95% concordance with KL grade. While it is tempting to rely on contact stress as a measure of anatomical reduction quality, and PTOA risk, computing contact stress is a non-trivial task. Conversely, measurement of articular step-off is a routine clinical task using either radiographic or CT imaging. The aim of this study was to compare the effectiveness of articular step-off vs. FEA contact stress computation as predictors of KL grade, to ascertain whether the additional time and expense required for contact stress measurement is justified. Articular step-off is measured using a 2D measure analogous to routine clinical measures and an advanced 3D measure to capture the entire joint.

Methods: Two measurement techniques were applied to measure articular step-off in eleven fractured ankles for which contact stress had been previously computed. All measures were computed from post-operative CT scans. The first set of measurements was performed by a trained orthopaedic surgeon, using a radiologic imaging workstation to emulate the routine clinical assessment (Fig 1). The surgeon was instructed to manually measure every articular step-off and gap in both the coronal and sagittal plane CT slices. Of these, the largest step-off or gap was recorded as a single measure for each plane.
The second measurement technique involved computing a full 3D deviation map comparing the articular surface of the fractured bone to its intact contralateral (Fig 1). This was done to find a “best case” articular step-off metric that takes into account the full 3D surface of the bone and not just specific points selected by the orthopaedic surgeon. Segmentations of both the post-op fractured and intact contralateral bones were performed in Osirix (http://www.osirix-viewer.com) imaging software. Each of the resulting surfaces were repaired and smoothed in Geomagic Studio (Geomagic, Research Triangle Park, NC). Each intact tibia model was registered to its fractured counterpart using the iterative closest point (ICP) algorithm. The intact articular surfaces were manually segmented into individual fragments to match the fracture pattern of their corresponding fractured limbs. These “fragments” was taken from their intact position to their fracture reduced position using the ICP algorithm (Fig 2). The surface model of each fragment in its intact pose and the rigid 4x4 transformation to its fractured pose were saved and loaded into MATLAB 2014a (Mathworks, Natick, MA). Step-off was determined by computing the point-to-point difference between the fragments in intact and fractured positions. The mean and maximum of the distribution of differences were examined as potentially useful metrics of articular step-off.

Figure 1. The three measurements compared in this study were manual measurements of articular step-off on CT (left), a 3D displacement measure of each fragment from its intact configuration (center), and chronic contact stress exposure previously measured using FEA.
The contact stress metric used was computed in a previous study examining the relationship of contact stress and KL grade [3]. That study created a FE mesh of the post-op talocrural joint for each subject. Each of the models was run through 13-step flexion-extension arc representing the stance phase of gait, with loading scaled to subject bodyweight. FEA results were used to compute a contact stress-time over-exposure metric for each subject, where the percentage of the total contact area exceeding a contact stress-time threshold was recorded. Contact stress-time over-exposure was computed using a contact stress damage threshold of 4.5 MPa and an exposure threshold of 3 MPa-s. These results were correlated with 2-year post-operative KL grades using Spearman’s correlation coefficient. Statistical significance was set at a p-value of <0.05.

**Results:** Step-off and contact stress-time over-exposure were computed successfully for all 11 cases. Aligned fragment geometries from the full 3D measure had excellent visual correspondence to the post-op fractured scan. The clinical measure of articular step-off had a mean value across all 11 cases of 5.6±4.9 mm. The mean and maximum values of 3D step-off were 2.4±1.7 mm and 6.3±4.1 mm. Mean contact stress-time over-exposure found 41.8±10.5% of the contact area exceeding the contact threshold over-exposed. Computed correlations with KL grade are listed in Table 1. As expected, the highest correlations were associated with the most comprehensive measures of step-off and contact stress.
Discussion: Although the displayed results show that the clinical measure of articular step-off was not significantly correlated with KL grade, the 3D step-off measure and contact stress-time exposure metric both had very similar correlations with KL-grade. The 3D step-off measure has a higher correlation than the clinical measure, presumably because it is able to use the intact bone as a reference. From this, the 3D step-off can compute not only local incongruities but changes in the overall shape of the joint such as pinching or widening of the articular surface, allowing the 3D metric to detect instability as well as incongruity. This is supported by the higher correlation of mean 3D step-off to KL-grade than max step-off, indicating that an overall global measure is of higher importance than a single peak measure. The clinical measure is much more analogous to the maximum articular step-off value, as it only captures the single largest step-off collected by the clinician.

Based on these results studies measuring step-off similarly to the discussed clinical measure may want to consider other more robust methods, especially accounting for inter-rater variability from similar studies [1]. The 3D step-off measure may be useful as a predictor of KL grade at 2 year follow-up, in studies where it is infeasible to compute FEA contact stress across the cohort of subjects. However, the 3D step-off method requires significant user interaction and remains to be validated for inter-user reliability. Computing 3D step-off also requires a high quality segmentation of both the post-operative fractured limb and its intact contralateral, obtaining CT scans of a healthy intact may be difficult due to current radiological standards and practices or impossible in cases of bilateral trauma. This study was limited by the small number (eleven) of subjects and the inclusion of only one joint. Future work with larger cohorts of subjects and including multiple joints may provide better information as to the relationship between contact stress, and articular step-off in prediction of radiographic PTOA.

Significance: The results of this study suggest that typical clinical measures of articular step-off following fracture reduction may be insufficient for prediction of outcomes. More thorough 3D measures of step-off or contact stress may be required for optimal prediction of PTOA outcomes.

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