INTRODUCTION

Post-traumatic osteoarthritis (PTOA) following an articular fracture is partly explained by contact stress aberrations associated with imperfect fracture reduction [1]. However, the tight association between residual fracture incongruity and acute fracture severity makes it necessary to evaluate large numbers of patients to understand the relative role of these factors in PTOA development.

Prior assessment of contact stress exposure utilized patient-specific finite element analysis (FEA) to study fractured ankles after reconstruction. Promising correlations were made between aberrant contact stress distributions and PTOA development in a relatively small group of patients (n=11) [1]. Additional enrolled patients were not able to be analyzed largely due to numerical convergence issues inherent in contact FEA, suggesting that it is impractical for use in larger studies.

An expedited analysis approach has been developed for evaluating patient-specific articular contact stress distributions from CT. This method involves semi-automated segmentation, automated model alignment to a weight bearing apposition, and use of an elastic contact algorithm.

METHODS

Semi-automated segmentation of tibia and talus
Ankle joint surface segmentation from the post-reduction CT is difficult due to the relatively low signal contrast between closely opposing surfaces, abrupt fracture incongruities, and fixation hardware metal artifact. To address these challenges, a user-guided segmentation algorithm has been developed using a 3D watershed transform, implemented in MATLAB (Fig. 1).

Alignment to weight bearing apposition
Due to the fact that the patient is supine during CT scan acquisition, the tibia and talus bones need to be aligned to a load-bearing stance. An iterative closest point (ICP) algorithm is used to align the segmented bone surfaces to template surfaces of an intact weight-bearing apposition. This approach is implemented in MATLAB, facilitating direct integration with the segmentation procedure, as well as with subsequent contact stress evaluation. Following the ICP alignment, a vertically oriented settling load is applied to seat the tibia (Fig. 2), using an elastic contact algorithm.

Expedited contact stress assessment
Following alignment and settling, the joint is driven through an expedited contact stress analysis routine, involving a 13-step flexion-extension cycle representing the stance phase of level gait. Contact stresses are calculated using a rigid body spring modeling algorithm implemented in MATLAB. Contact is determined using a pressure over-closure relationship between the talar and tibial cartilage.
surfaces, with spring deformation being related to the level of over-closure (Fig. 3) [2]. Engendered loads and moments are then used in a load balancing algorithm on the tibial surface. The simulation is run in load control, scaled to patient body weight, with the tibia constrained in all directions other than superior-inferior translation, and the talus constrained in superior-inferior translation and flexion extension.

To assess the method’s predictive value, metrics of contact stress-time exposure and of areas of elevated contact stress were compared to PTOA development, judged by a radiographic score (KL grade ≥ 2) at a minimum 2-year follow-up [3].

RESULTS AND DISCUSSION

The 3D watershed algorithm performed well, taking approximately 5 minutes to complete. The mean unsigned difference between segmentations obtained using this new method and previous iso-surfaced and hand edited segmentations was 0.55±0.22 mm.

Alignment of the ankle to a neutral loaded apposition using the ICP algorithm required 1-2 minutes of computational time. This alignment was highly reproducible and agreed with prior expert alignments performed on the ankles (Fig. 4).

The elastic contact algorithm provided results for the entire 13-step gait cycle of an ankle within 2-3 minutes of computation time. The difference between the expedited and FEA contact stress-time exposures was 0.03 (±0.02) MPa-s, when evaluated on identical models on a point-by-point basis. Many of the larger differences (>1 MPa) occurred near the edges of contact, at sites where only one methodology predicted contact. Using the previous FEA methods, a contact stress-time-area metric agreed with patient KL grade and OA status (KL ≥ 2) at concordance rates of 95% and 100%, respectively [1,3]. By comparison, when used on the same ankle models the elastic contact algorithm was able to obtain a 97% KL concordance and 100% OA concordance, thus showing equivalent predictive ability for PTOA development.

CONCLUSIONS

These expedited contact stress evaluation methods show promise for use in large studies involving hundreds of patients. The expedited segmentation, alignment, and contact stress analysis components all performed in an equivalent manner compared to the previous FEA study, with a fraction of the required time and user intervention.

REFERENCES


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