

SEMI-AUTOMATIC 3D VIRTUAL RECONSTRUCTION OF SIMULATED COMMUNUTED ARTICULAR FRACTURES

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INTRODUCTION

High-energy comminuted peri- and intra-articular fractures involving multiple bone fragments pose a substantially more difficult surgical challenge to reconstruct than do more commonplace low-energy fractures. It can be difficult for the surgeon even to ascertain how the bony fragments should fit back together to restore the original anatomy: an activity that in essence involves solving a three-dimensional (3D) puzzle. In addition, the further the fragments are displaced, and the more they are interspersed, the more challenging it is to know in what sequence they might best be repositioned, so as to minimize additional surgical trauma to already severely injured surrounding soft tissues. These issues are especially important given the purported benefits of less invasive surgical techniques.

Virtual reconstruction with 3D puzzle solving methods can provide objective descriptors of comminuted articular fracture severity, and can serve as a valuable blueprint for surgical reconstruction. The complexities of natural bone specimens confound the development of this technology, and conventionally acquired clinical CT scan data afford less-than-ideal spatial resolution of fragment surfaces. Toward clinical application, algorithmic developmental work on 3D puzzle solving benefits from more precise data. Therefore, the purpose of this work was to develop a platform that utilized test specimens whose fragment geometries were precisely quantifiable so that a novel method for fracture reconstruction could be tested. It was hypothesized that an accurate fracture reconstruction would be possible by matching fragment periosteal surfaces to an intact (or mirrored contralateral) template using a semi-automated algorithm.

METHODS

A methodology for generating fragmentation-dispersal patterns typical of comminuted orthopaedic fractures in non-biologic replicas of normal tibial geometry was developed. This well-behaved platform provides an ordered progression in complexity to guide ongoing algorithmic developments in the 3D puzzle solver (Figure 1).

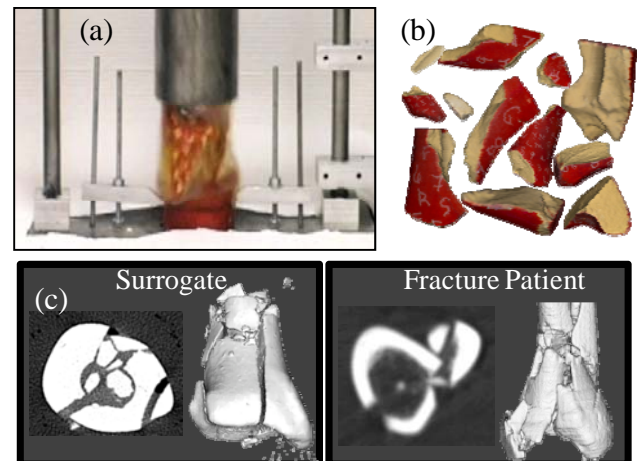


Figure 1. An instrumented drop tower (a) was used to create the comminuted fracture (b), similar to clinically observed (c).

Five identical replicas of human distal tibia anatomy, derived from CT, were machined from blocks of high-density polyurethane foam [1]. This material exhibits mechanical and fracture behavior comparable to that of human cortical bone, and when suitably doped with BaSO₄, it displays similar x-ray and CT appearance [2]. A talus analog molded of polymethyl methacrylate provided an anatomically corresponding proximal surface for tibio-talar contact, and a flat distal side for flush impactor contact. These test specimens were then encased together in a gelatin to simulate the surrounding soft tissues of the distal shank.

Fracture impacts were delivered using an instrumented drop tower. A heavy steel cylinder of parametrically selected mass was released at a selected height to deliver nominally 200 Joules of kinetic energy (Fig 1.a). Pre- and post-fracture fragment geometries were separately obtained using laser (Fig 1.b) and CT scans (Fig 1.c).

The reconstruction algorithm began with periosteal surface identification. Since the tibia analog's outer surface was colored red before impact, it could be segmented from the fragment's fractured surface using an automatic texture classification program. The tibia was then methodically reconstructed by matching fragment and intact periosteal surfaces using Geomagic Studio Software. This technique started by aligning the fragment with the largest surface area to the intact template using an iterative closest point algorithm (ICP). The algorithm proceeded by individually aligning the remaining fragments, from largest to smallest. The accuracy and speed of alignment was improved by iteratively reducing the ICP algorithm's searchable area over the template once a fragment was placed. The accuracies of the puzzle solutions were then quantified by calculating distances between the intact and the reconstructed surfaces.

RESULTS AND DISCUSSION

The fracture morphologies generated by this protocol simulated clinical fracture cases (Fig 1.c). The replica tibias were fractured into 8 to 14 discrete fragments of varying sizes, with 2-4 of those being articular. Post-fracture fragment volumetric comparison showed that approximately 95% of the pre-fractured volume was recovered as manipulably-sized fragments. Figure 2 illustrates the puzzle solutions obtained for the 5 tibias. Computational surface alignment yielded precise geometric reconstructions, with alignment accuracy ranging from 0.03 to 0.2 mm.

Intra-operative navigation tools exist to aid in the reconstruction of long-bone fractures, but these systems require a high degree of user interaction and are of limited value for the complex geometries of comminuted articular fractures. 3D puzzle solving methods can help to fill this need, providing a pre-surgical blueprint for reconstruction.



Figure 2: Reconstruction results for 5 replicas

The methodology for recreating comminuted fracture geometries in a suitable surrogate material presented here provided idealized data that facilitated the advancement of a semi-automated periosteal alignment algorithm. With its impressive accuracy and potential to be fully automated, this algorithm is likely to one day be an integral part in the virtual reconstruction of actual clinical cases. Of course many challenges remain to be addressed before this is possible. With further advancement, this nascent technology has the potential to significantly enhance the way in which surgeons reconstruct comminuted intra-articular fractures.

REFERENCES

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