A Computational/Experimental Platform for Investigating Three-Dimensional Puzzle Solving of Comminuted Articular Fractures

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Abstract

Reconstructing highly comminuted articular fractures poses a difficult surgical challenge, akin to solving a complicated three-dimensional (3D) puzzle. Pre-operative planning using CT is critically important, given the desirability of less invasive surgical approaches. The goal of this work is to advance 3D puzzle solving methods toward use as a pre-operative tool for reconstructing these complex fractures. Methodology for generating typical fragmentation/dispersal patterns was developed. Five identical replicas of human distal tibia anatomy, were machined from blocks of high-density polyetherurethane foam (bone fragmentation surrogate), and were fractured using an instrumented drop tower. Pre- and post-fracture geometries were obtained using laser scans and CT. A semi-automatic virtual reconstruction computer program aligned fragment native (non-fracture) surfaces to a pre-fracture template. The tibias were precisely reconstructed with alignment accuracies ranging from 0.03-0.4mm. This novel technology has potential to significantly enhance surgical techniques for reconstructing comminuted intra-articular fractures, as illustrated for a representative clinical case.

Keywords

articular fracture comminution; virtual surgical reconstruction

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INTRODUCTION

Most commonplace fractures of bone are readily managed using well-established treatments. Considerations differ markedly for high-energy injuries in which bone is comminuted into a large number of fragments. During these traumatic events (e.g. motor vehicle accidents, ballistic impacts, falls from a height), where substantial energy is delivered at a high rate, bone fragments are propelled through the surrounding soft tissue, severely disrupting the osseous and soft tissue anatomy (Figure 1). Oftentimes, dozens of individual fragments are involved, many of them displaced appreciably from their site of anatomic origin, and interspersed in a complex geometric pattern. It is especially troublesome when fractures extend into an articular joint. Such fractures carry considerable long-term morbidity and treatment cost (Brown et al. 2006;Thordarson 2000). Clinical evidence suggests that accurate fracture reduction is very important, since incongruities alter the articular contact stress and may predispose the joint to degeneration (Marsh et al. 2002;Matta 1996), but the specific criteria for acceptable reduction in different joints are a matter of controversy in orthopaedic traumatology.

The surgeon reconstructing a comminuted fracture faces a problem very much akin to solving a "three-dimensional puzzle," albeit with several additional complexities. Muscle forces, combined with complex fragment displacements, intervening soft tissues, and interaction between fragments and fracture surfaces, all serve to make it difficult to mobilize and reposition the fracture fragments. To partially or completely restore the osseous anatomy, traditional surgical treatment (open fracture reduction) exposes the fragments by a dissection of the damaged soft tissue envelope. The surgeon can then directly assess and reduce the fragments by trial and error. The fracture is considered to be reduced when the surgeon judges that an optimal fit has been obtained between all relevant fragments, giving special attention to restoration of the articular surface. Unfortunately, any "errors" during this trial and error prolong the procedure and increase secondary trauma to the fragments and the surrounding soft tissues. This provides impetus for developing less invasive surgical techniques to more predictably reduce displaced comminuted fractures.

Accurate and precise pre-operative planning, building upon modern medical imaging and upon knowledge of the pre-fracture anatomy, can provide information instrumental for performing less invasive articular fracture surgery. Computational techniques hold strong potential to contribute in this area. Algorithms for matching objects based on their shapes have been applied in the past to the assembly of (2D) jigsaw puzzles (da Gama Leitão and Stolfi 2002; Freeman and Garder 1964; Wolfson et al. 1988). However, jigsaw pieces have similar sizes with easily identifiable sites that need to be matched. Solving more difficult puzzles involving physical fracture surfaces is an emerging area of research (Cao and Mumford 2002; McBride and Kimia 2003; Üçoluk and Hakk Toroslu 1999; Willis 2004; Willis and Cooper 2004; Willis et al. 2003). Examples of successful puzzle solving in full 3D situations remain limited (Kong and Kimia 2001; Papaioannou et al. 2001; Üçoluk and Hakk Toroslu 1999). The primary path taken in dealing with fragments of arbitrary shape has been to base assembly efforts on matching and aligning the fragments' break curves, i.e., the edges of the surfaces along which the fragments physically broke apart (Kong and Kimia 2001; Üçoluk and Hakk Toroslu 1999). The initial stimulus for that technology had been the reconstruction of culturally/historically important relics such as broken pottery and broken sculptures, recovered from archaeological sites (Cooper et al. 2002). For that type of application, computational puzzle solution has taken as its input the 3D surface geometry of each of the recovered fragments quantified by laser scan, with geometric reconstruction performed by matching individual fracture surfaces and fragment boundaries.

Implementing puzzle solving for the orthopaedic situation of highly comminuted intra-articular fractures involves several considerations not encountered in precedent archaeological work. Bone fragment surfaces tend to be more highly irregular, and they can frequently lie in very close proximity to one another (or even in partial contact), making discrimination of individual fragments sometimes difficult. To compound matters, the boundaries of the bone fragments in clinical fracture cases must be extracted by segmentation of CT scan data, which are subject to partial volume effects. Fortuitously, two aspects of bone fractures are actually more advantageous than for archaeological fractures. First, bone fragments have spatially varying distributions of density, which can be measured from CT scan data (Hounsfield Units) and therefore constitute additional basis for registration. Second, for fractures of an extremity, the intact contralateral bone represents a reasonable mirrored template against which to reconstruct the fracture (Auerbach and Ruff 2006; Plochocki 2004).

The literature regarding virtual reconstruction of bone fragments is relatively sparse, compared to the very large body of research on the topics of bone segmentation and medical image registration. Early efforts in this area included a technique for reconstructing a simple two-fragment bone fracture (Ron et al. 2001). More recent work has focused on developing algorithms to support image-based reconstruction systems (Scheuering et al. 2001; Winkelbach and Wahl 2008), including even a complete fracture reassembly environment (Harders et al. 2007). However, these methods require the user to manually reposition fragments, a daunting task for highly comminuted fractures. Willis et al. recently reported methodology for semi-automatic reconstruction of highly comminuted bone fractures, developed to aid in treatment planning (Willis et al. 2007). The software aligns bone fragment fracture surfaces derived from segmentation of volumetric CT scan data. The user interactively selects fracture-surface patches, in pairs that coarsely correspond, after which an optimization step is performed to automatically solve the corresponding N-body rigid alignment problem. In such a virtual interactive environment, the user is able to influence the reconstruction process, and to examine multiple potential reconstruction scenarios. In subsequent development (Zhou et al. 2009), new algorithms were introduced to improve accuracy of anatomic restoration, using an alignment functional that allowed idiosyncratic geometric surface variations (ridges and valleys) to more heavily influence the final alignment solution, yielding results which were highly encouraging visually.

With computer assisted surgery becoming more common in orthopaedics, surgeons are increasingly recognizing the utility of pre-operative planning, especially for procedures calling for precise spatial manipulations in situations of high geometric complexity, such as in highly comminuted intra-articular fractures. 3D puzzle solving has the potential to be an integral part of these new technologies. However, the complexities of working with natural bone specimens confound systematic development of this technology, and conventionally acquired clinical CT scan data afford less-than-ideal spatial resolution of fragment surfaces. As a next step toward clinical application, algorithmic refinements of 3D puzzle solving would benefit from the availability of more precise and controlled data. Therefore, the purpose of this work was to create a development platform, utilizing test specimens whose fragment geometries are precisely quantifiable, so that the performance of puzzle solving methods for fracture reconstruction could be assessed against an objective gold standard. Using replica distal tibias machined from a bone surrogate material, a novel puzzle solving approach was taken to restoring the original anatomy by aligning the fragments' native (non-fracture) surfaces to a pre-fracture template. After developing and assessing this algorithm in replica tibias, it was applied retrospectively to a severely comminuted tibial plafond fracture.

METHODS

Fracture fragment generation

Methodology was developed for generating fragmentation/dispersal patterns typical of comminuted articular fractures, but in surrogate test specimens (Figure 2). Using anatomy derived from CT, five identical replicas of a human distal tibia were machined from blocks of high-density polyetherurethane foam. This material was selected because it exhibits structural and fragmentation behaviour comparable to that of native human cortical bone, and when suitably doped with $BaSO_4$, it displays similar x-ray and CT appearance (Beardsley et al. 2000). An innovative rapid machining technology (Frank et al. 2004) was used to recreate the distal tibia geometry, working off models generated from CT segmentations of intact anatomy. The processing instructions for the computer numerically controlled machining were derived using advanced geometric algorithms for toolpath planning and fixturing (Frank et al. 2004).

The external surfaces of the surrogate distal tibias were indelibly colour-dyed, so that fracture-liberated surfaces could be distinguished from native surface. The native-equivalent surface was also marked with alphabetic graffiti, to enable later unambiguous determination of the original location of fracture-generated fragments. A desktop 3D laser scanner (NextEngine Model 2020i[†]; NextEngine, Inc., Santa Monica, CA) was then used to capture the geometry and surface appearance (geometry and colour texture) of the surrogate tibias. Finally, these surrogate test specimens were encased in cylinders of dense hydrocarbon gel (a clear, highly occlusive emollient from Calumet, L.P) designed to replicate the resistance to bone fragment traversal through surrounding soft tissues during the fracture event. The entire physical test preparation was then CT scanned en bloc.

The test specimens were next impacted using an instrumented drop tower, to cause highly comminuted fractures involving 10-15 fragments. A steel cylinder (7.6 kg mass) was released from a selected height to deliver the necessary (empirically determined) kinetic energy. A talus analog, molded of polymethyl methacrylate, provided an anatomically matching proximal surface for tibio-talar contact, and had a flat distal side for flush impactor contact. The fractured specimens were then again CT scanned, with the fragments at their spontaneously-displaced/interspersed positions in the gel. Subsequently, the fragments were removed from the gel, and their surface geometries were individually laser-scanned (gold standard for fragment surface geometry). This ordered developmental platform provides clinically relevant data to improve the effectiveness of 3D puzzle solving algorithms, without hindrance by the many confounding factors involved in dealing with actual bony fractures.

3D puzzle solving methods and their implementation in surrogate specimens

Puzzle solutions were obtained using a semi-automatic fragment reconstruction approach (Figure 3). The reconstruction algorithm began with native surface identification performed in an interactive environment. Since the tibia analog's outer surface was coloured red prior to impact, that pre-existing surface could be reliably segmented from the fragment's de novo fractured surface, using an automatic texture (colour) classification program. The results from this step served as the gold standard from which alternative segmentation algorithms could be systematically investigated.

[†]Manufacturer-supplied product specifications: Geometry point density on target surface is 80 points/cm. Texture density is 160 points/cm. Dimensional accuracy is ±0.13 mm.

Since human fractures of course cannot be segmented based on colour, native surfaces were also identified from geometric information. During high-energy impact loading, bone fractures as a brittle solid, and its fragment fracture surfaces tend to be relatively flat. Looking ahead to that issue clinically, surrogate fragment surfaces were segmented into discrete patches, by developing a region-growing algorithm that propagated patches up to boundaries of high curvature (Figure 4). The algorithm started with the seeding of a random facet on the fragment's surface representation (triangular mesh), and then proceeded by analyzing how neighbouring facets were oriented relative to the seeded facet. If a neighbouring facet's surface normal direction deviated by less than a threshold angle from the seeded region, the facet was annexed. A facet whose normal deviated from the seeded region by greater than the threshold was classified as an edge, and not analyzed in future iterations. This algorithm continued until the grown region no longer had any neighbouring facets that satisfied the surface normal criterion. A new region was then seeded on a randomly chosen as-yet unvisited facet, and the process repeated. The required surface normal deviation threshold was determined empirically, and was found to consistently be approximately 10°. Due to the tibia's shape and fracture behaviour, the discrete patch with the largest area on a given fragment was consistently found to be the native surface.

The tibia was then methodically reconstructed by matching each fragments' native surface to the intact template using Geomagic Studio Software's built-in iterative registration function (Geomagic, Inc., Research Triangle Park, NC U.S.A.). This function started by automatically bringing the fragments' surfaces into rough alignment with the template, by aligning their centres of mass and principal axes. However, some fragments lacked sufficient geometric attributes for this step to execute automatically. This occurred when attempting to match diaphyseal fragments that had cylindrically shaped periosteal surfaces, or that had a surface area less than 2 cm^2. In these instances, rough alignment had to be done manually, with the user designating three pairs of surface points that were in nominal correspondence. After the automatic or manual rough alignment, fragments were sampled at a user-specified resolution, and the closest points computed on the intact template for each point sampled. Next, an iterative closest point (ICP) algorithm was executed: the sums of squares of distances between the sample pairs were minimized over all the rigid motions that could align the two objects (Besl and McKay 1992). Having done this, the program re-computed the closest points on the template and established the final spatial alignment transformation. Using this alignment approach, the intact bone was reconstructed, starting with the fragment with the largest surface area. The puzzle-solving algorithm proceeded by individually aligning the remaining fragments, moving in turn from largest to smallest. The accuracy and speed of alignment were improved by successively reducing the ICP algorithm's searchable area, by deleting regions of the template that had already been successfully matched to a fragment.

Computational puzzle solutions were thus executed for each of five surrogate distal tibia replica fracture cases. The accuracies of the puzzle solutions were quantified by calculating the distances between the intact template and the fragments' native surfaces, and the distances between mating interior/fracture surfaces. The difference between the spatial volume enclosed by the aligned bone surrogate fragments versus that of their intact (pre-fracture) specimens was used as an additional measure of surface reconstruction accuracy.

RESULTS

The fracture morphologies generated by the surrogate testing protocol successfully replicated the types of morphologies seen in clinical fracture cases. As with tibial plafond fractures, the replica tibias' articular surfaces were fractured anterior-posteriorly and/or medial-laterally through the weight bearing region. The replicas fractured into between 8

and 14 discrete fragments of varying sizes, with 2-5 of them being articular. Post-fracture fragment volumetric comparison showed that approximately 95% of the pre-fractured volume was recovered in the form of manipulably-sized fragments. The remaining volume was accounted for by "dusting" (crumbling of material), and/or by the need to discard fragments that were too small ($\sim0.5cm^3$) to be feasible for physical manipulation in a surgical setting. In addition to the problematic laser scanning of these small pieces, fragments less than this size are typically impractical to surgically reduce and fix. Figure 5 illustrates the puzzle solutions obtained for the five replica tibias. With respect to the intact template, computational surface alignment yielded precise geometric reconstructions, with RMS accuracy of fit to the whole intact template ranging from 0.03 to 0.2 mm (Figure 6). Since clinical outcomes are especially affected by residual articular incongruities, the alignment accuracy specific to the weight-bearing region was separately calculated. Although some regions were plastically deformed during the impact event, the articular surface was congruent and matched to the intact template within an average accuracy of 0.13mm. Proximities of internal (inter-fragmentary) fracture surfaces in the surrogates were less accurate, averaging 0.85mm, and they demonstrated a bimodal distribution. Internal fracture surfaces tended to be either very well aligned to one another, or else they had distinct gaps, in some instances exceeding 1mm.

DISCUSSION

Existing intra-operative navigation tools developed to aid in the reconstruction of long-bone fractures are not designed to puzzle-solve complicated fractures. While useful for fixation planning for simple fractures, these early-generation systems are unable to deal with the complex geometries of comminuted articular fractures. Without computational aid, surgeons dealing with complex fractures have to rely on their years of accumulated experience and training, to cognitively plan the reconstruction from a stack of 2D CT slices or from a 3D volumetric rendering thereof. This task is particularly challenging in comminuted fractures where fragments are appreciably displaced, and where some fragments may even be missing. While surgeons try to position fragments such that the weight-bearing surface is as smooth and congruous as possible, results are oftentimes substantially imperfect. The virtual 3D puzzle solving methods here reported hold great potential for improving the care of these difficult injuries. By having a blueprint for restoring the original anatomy, it becomes possible for the surgeon to perform less extensive surgical dissections, and to lower the number of mismatches of candidate fragments, while still achieving accurate fracture reconstructions.

Due to the novelty of the 3D puzzle solving approach, its successful development benefits from an ordered progression in puzzle complexity. The creation of representative comminuted fracture geometries in a suitable surrogate material provides clinically realistic data to facilitate advancement of fragment alignment techniques. Although alignment to an intact template offers an effective strategy, it is also important to consider how well the fragments' internal fracture surfaces fit together. If substantial inter-fragmentary gaps would exist clinically after native surface alignment, additional fragment repositioning or supplemental bone grafting might well be needed for adequate stability. While this was not an issue with most fragments in the present surrogate cases, the techniques reported for internal fragment alignment accuracy in this study could straightforwardly identify situations of bone loss (either existing, or necessitated by contamination or necrosis requiring fragment removal), and thereby provide the surgeon with a precise description of the void's geometry. To puzzle solve such cases, both native surface and inter-fragmentary alignments need to be taken into account, thus requiring a dual strategy that simultaneously combines both matching to the intact contralateral template and alignment along inter-fragmentary boundaries.

To illustrate the clinical potential of this technology, the above-described 3D puzzle solving methods were applied to retrospectively reconstruct a typical intra-articular fracture. The case involved a tibial plafond fracture sustained by a 38 year old female who was in a high-speed motor vehicle crash. Fragment geometries were extracted from pre-operative clinical CT data, obtained with 0.3mm in-plane resolution and 0.5mm slice spacing. Using 3D image analysis techniques, the severely comminuted tibia (Figure 7a,b) was segmented into eleven discrete fragments (Figure 7c), five of which were articular. The intact template was obtained by digitally reflecting the intact contralateral tibial CT segmentation data about a mid-sagittal plane of symmetry.

Using the methodologies developed in the surrogate platform, the fractured limb was then reduced to its pre-fractured state (Figure 7g). The accuracy of reduction obtained over the majority of the surface was similar to that in the surrogates. Average native surface aligned accuracy was 0.53mm, and the inter-fragmentary distances between aligned fracture-patches were between 0.1 to 0.7mm (Figure 7h). A few surfaces had separations beyond that range, mostly concentrated in the interior of the metaphysis, possibly explained by minor cancellous bone compaction. Better internal alignment quality between surrogate versus clinical fragments was also probably influenced by the differences in the quality of bone surrogate segmentation attained by laser scan versus the need to have segmented the clinical case from CT data.

Although there is room for additional improvement, the results from this reconstruction case illustrate this methodology's clinical applicability. While the joint surface was surgically reduced with a high degree of accuracy, the plafond was tilted posterior approximately 30° (Figure 7d). As with many fracture cases, the clinician likely faced significant intra-operative challenges that prevented a perfect reconstruction. In addition to the task of solving a complicated 3D puzzle with limited visibility, the surgeon had to manage other operative issues while attempting to minimize secondary trauma. A pre-operative blueprint for reconstruction would aid in this situation (Figure 7f,i). The surgeon could use that ideal reconstruction as a reference for planning their own reconstruction, that accounts for various intra-operative complexities. For instance, the surgeon would have likely recognized the structural instability in the virtual reconstruction's posterior metaphysis, and consequently, either planned an alternate fragment configuration, a different fixation technique, or used some grafting. It is in this supplemental capacity that puzzle solving can provide a distinct advantage to the surgeon: useful pre-operative knowledge.

The above-described algorithm for matching fragment native surfaces to an intact template is the computational analog of how clinicians intuitively reconstruct comminuted fractures. But, rather than the necessity of trial-and-error during the course of the surgery, the algorithm can help surgeons precisely quantify and visualize difficult reconstructions before an incision is made. This would permit the surgeon to contemplate less extensive surgical dissections, while still achieving accurate fracture reconstructions. While useful in its current capacity, puzzle solving has the potential to mature into an essential component for use in treating highly comminuted articular fractures. Presently, puzzle solving provides only final destination information from a pre-operative CT. A future step for 3D puzzle solving could be intra-operative integration, to help guide the actual surgical reduction in real time. This would require substantial developments not only in the puzzle solving algorithms themselves, but also in the imaging modalities that link the virtual and physical worlds. As surgical navigation and imaging systems become more advanced, this long-term vision becomes more feasible. In the short-term, puzzle solving's pre-operative utility is not limited to simply generating the ideal reduction. It also provides input data for computationally modelling possible fixation constructs, and for assessing their initial mechanical stability.

Of course, several challenges remain to be addressed prior to practical implementation. Current CT segmentation techniques are too labour intensive for routine clinical use, and so will need to be expedited. Also, clinical execution of a planned reconstruction needs to respect broader anatomic constraints: the surgical access site, the presence of nearby neurovascular structures, the sequence in which fragments can be optimally reduced, etc. In addition, current puzzle solving algorithms do not account for plastic deformation, which can occur in some fractures. While certain conditions may produce cancellous bone impaction/compression, there is evidence that healthy bone fractures as a relatively brittle solid during high-energy, rapid loading events like those producing the tibial plafond fractures (Anderson et al. 2008). This may not be the case for some older or osteopenic patients, but this particular injury predominantly occurs in a young and otherwise healthy population. Nevertheless, we aim to broaden the types of injuries that can be puzzle solved by developing new algorithms that more explicitly consider inter-fragmentary alignment. Presently, however, to further improve its clinical relevance, the alignment algorithm is being advanced such that priority is given to the articular surface, the most biologically important surface to restore in order to forestall joint degeneration. Such limitations notwithstanding, the results from the present study suggest that 3D puzzle solving offers a powerful new tool for enhancing surgical reconstruction of complex peri-articular fractures.

Acknowledgments

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Figure 1.
Radiographs and volumetric rendering from a high-energy tibial plafond fracture with severe comminution (~15 fragments)
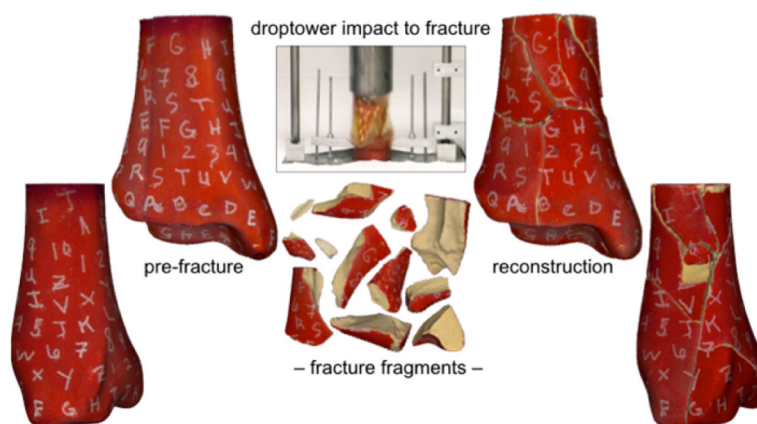
Figure 2.
An instrumented drop tower was used to create comminuted fractures, similar to those observed clinically. Distal tibia replicas were 3D laser scanned prior to fracturing, and the fragments were scanned afterwards. Subsequent reconstruction was executed.
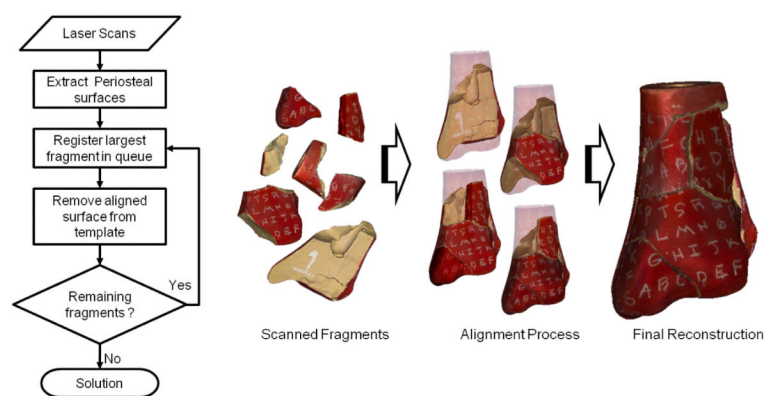
Figure 3.
A 12 fragment surrogate fracture puzzle solution is shown. Anatomic geometry is restored using a semi-automatic virtual bone fragment reconstruction system.
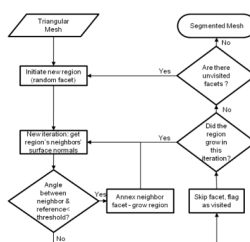
Figure 4.
Flowchart describing the fragment mesh surface segmentation algorithm.

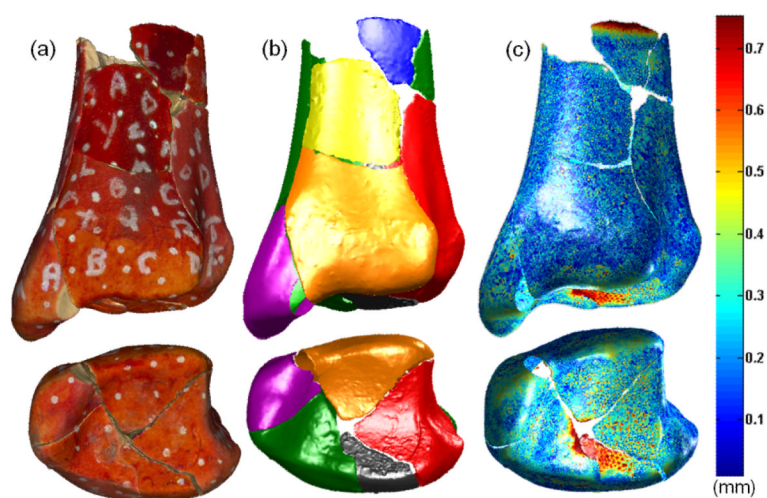**Figure 5.**
Reconstruction results for 5 replicas.

Figure 6.
Reconstruction of the whole bone (top row) and the articular surface (bottom row) is shown for a typical surrogate tibia (a). Individual segmented fragments are shown colour-coded (b). The pre- and post- fracture native surface distance deviation calculations (c) verified that the original anatomy was accurately restored.
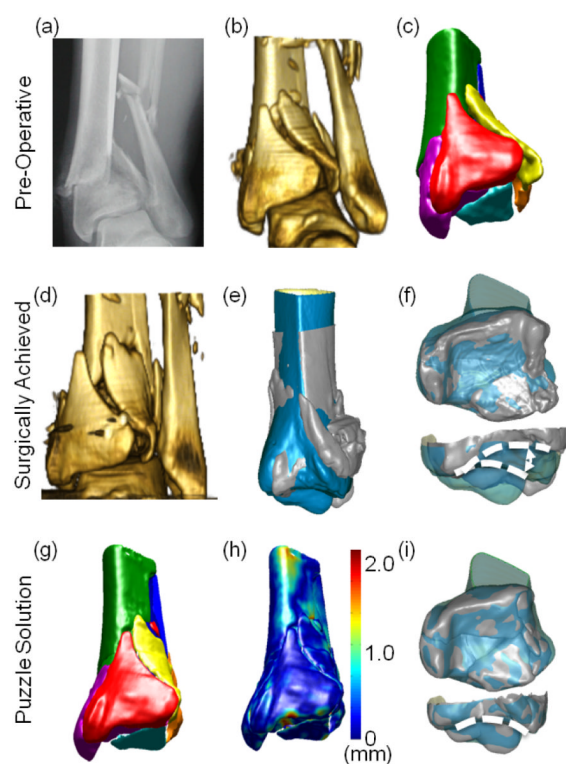
Figure 7.
Illustratively, surgically achieved and computer-assisted reconstruction results are compared for a clinical tibial plafond fracture (a,b,c). The achieved surgical reduction (d) did not restore normal anatomy (e, blue surface) since the articular surface was posteriorly tilted approximately 30° (f). The puzzle solution (g) restored anatomy with accuracies predominately within much less than 1 mm (h), and correctly aligned the articular surface (i).