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Semi-automatic Customization of Internal Fracture Fixation Plates

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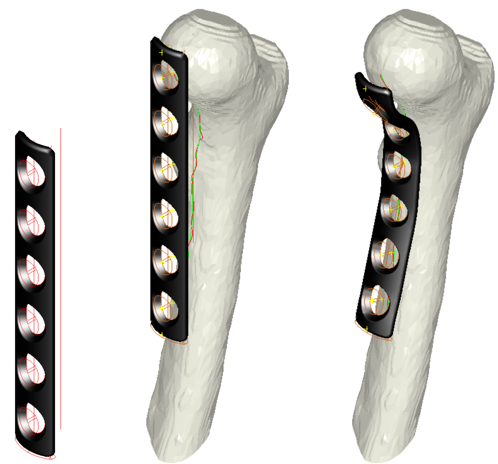
***Abstract*— A new method for customization of fixation plates for repairing bone fractures is proposed. Digital models of plates are typically available as CAD models that contain smooth analytic geometry representations including NURBS. With the existing pre-operative planning solutions, these models are converted to polygonal meshes and adapted manually to the patient's bone geometry by the user. Based on the deformed model, physical bending is then performed by the surgeon in operating room. With the proposed approach, CAD models are semi-automatically adapted using NURBS to generate customized plates that conform to the desired region of the bone surface of patients. This enables an efficient and accurate approach that is also computationally suitable for interactive planning applications. Moreover, the patient-specific customized plates can then be produced directly from the adapted CAD models with a standard CNC machine before surgery. This may dramatically reduce time spent in OR, improve precision of the procedure and as a result improve the patient's outcome.**

I. INTRODUCTION

This paper proposes a novel method for creating custom implant plates for Open Reduction Internal Fixation (O.R.I.F) type treatments for repairing bone fractures. Standard plates such as the one shown in Fig. 1 (a) are surgically placed to hold fractured bone segments together. The plates typically have to be deformed to fit a specific patient's bone surface geometry in order to better aid rehabilitation. The traditional approach for plate placement involves inspection of the fracture, aligning bone fragments to their original positions (reduction), physical bending of plates (adaptation) and placement to fit the fractured bone.

With the advent of non-invasive 3D imaging modalities such as CT and MR, there has been a recent impetus on computer assisted preoperative planning and customization of implants and surgical instruments. For example, preoperative planning in pelvic and acetabular fracture surgery is proposed in [2], [8], [9]. This development leads to less invasive and more accurate procedures, reduces burden on the surgeon during the operation, shortens time spent in the OR and ultimately improves patients' outcome. Modern orthopedic preoperative planning systems utilize information from scanned images of bones fragments to plan fracture reduction and fixation. Digital models of plates are typically available as Computer Aided Design (CAD) models that contain smooth analytic representations of the geometry of the models. The CAD models are first discretized to polygonal mesh representations in existing computer aided planning and customization tools [2]. Precision of the planning procedure is dependent on the accuracy of the mesh approximating complex plate geometry. High accuracy typically requires very fine sampling that leads to high computational cost. In addition, a CAD model of the new deformed geometry is required to manufacture a customized plate. The deformed polygonal meshes have to be reverse engineered to obtain CAD representations, which is a non-trivial task. Alternatively, standard plates may be physically adapted based on measurements from adapted meshes [2], which is very time consuming.



(a) (b) (c)

Fig. 1. (a) CAD model of standard off-the-shelf plate. (b) Initial interactive placement of plate in desired region. Patient bone geometry is obtained from CT image. (c) CAD model customized to conform to curved region of patient's bone surface.

We propose a new method for 3D computer assisted non-invasive plate customization that directly adapts the CAD representation to obtain customized CAD models. To the best of our knowledge, this is the first method to propose direct processing of CAD models without intermediate mesh representations for adaptation of fracture fixation plates. The Non Uniform Rational B-Spline (NURBS) [4] geometry representation is used to perform smooth accurate deformation. NURBS based geometry is manipulated by a set of control points. The deformation procedure is computationally more efficient since much fewer control points are required to manipulate NURBS-based plates; whereas typically, a very large number of polygons are required to manipulate accurate mesh based plate representations. The customized CAD models can then be directly used for manufacturing since NURBS is an industry standard for computer aided design and manufacturing (CAD/CAM) systems.

Fig. 1 shows a CAD model of a standard plate that is customized to fit the desired region of the bone. In this work, the adaptation process is guided by a curve on the

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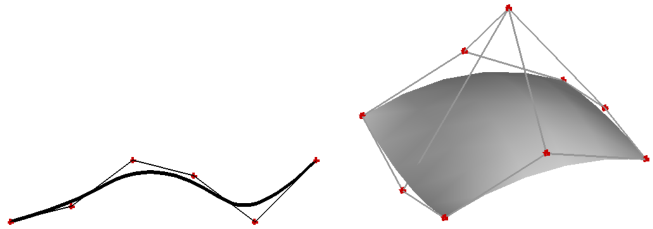
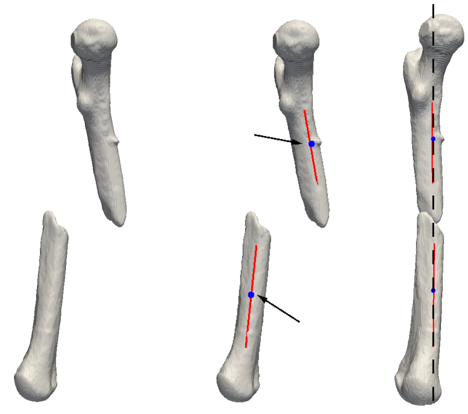


(a) (b)

Fig. 2. (a) NURBS curve. (b) NURBS surface. The smooth shapes of NURBS curves and surfaces are defined by relatively few control points shown in red.



(a) (b) (c)

Fig. 3. Interactive reduction. (a) Fractured femur bone fragments. (b) Interactive selection of alignment features in 3D. (c) Reduced bone fragments.

bone surface. However, the proposed ideas are quite general and hence extensible to other adaptation techniques (e.g., using guide surfaces). The aim of this paper is to present the feasibility and benefits of performing adaption directly with CAD representations.

II. BACKGROUND

A. NURBS representation

NURBS [4], [7] is a de-facto industry standard for representation of smooth curved geometry. It is based on piecewise polynomial or rational functions with the ability to represent freeform shapes of arbitrary degree and smoothness. NURBS curves and surfaces are manipulated by control points that intuitively define the resulting shape (Fig. 2).

B. Axial Deformation

Axial deformation [1] is a geometry representation independent technique that uses a parametric curve to guide deformation of an object. Transformations are applied to a set of points defining the geometry; control points for a NURBS curve or surface, or the vertices of a polygonal mesh. Axial deformation is used in the proposed work for deforming all curves and surfaces of a CAD model. Let $S(u)$ be the initial axis with a local frame defined at every point on the curve. A control point, P, is mapped to a point on the axis $S(u_P)$. Let the deformed curve be $D(u)$. The new location of the corresponding point P_d in the deformed shape is computed using $D(u_P)$ and its local frame. See [1] for details.

III. WORKFLOW

A. Overview

With the proposed workflow, the fractured bone fragments are converted from scanned images (CT) to polygonal meshes and the reduction procedure is performed so that bone fragments are placed in their original relative positions, as shown in Fig. 3. A guide curve is interactively computed on the meshes and used as the final deformed axis to perform axial deformation. The plate CAD model is imported and prepared for adaptation. A linear longitudinal axis of the plate is computed for initializing axial deformation. The plate and bone meshes are registered to an initial location (Fig. 1 (b)). The plate CAD model is then adapted based on the guide curve (Fig. 1 (c)). CAD model processing has been implemented using Open Cascade [6].

B. Fracture reduction

The goal of fracture reduction is to position bone fragments in their anatomically correct position, which is crucial in order to restore normal functionality after healing. In particular, for the femur bone reduction there are two major factors (a) axial alignment of the fragments and (b) correct periaxial angle measured between the femural head and the distal femur. Misalignment may cause severe pain, deformity and permanent discomfort to the patient, that in some extreme cases, may even require another correction surgery in the future. In order to prevent these complications, computer assisted systems are being currently developed and introduced into orthopedic surgery. Currently, most of the reduction planning is done in 2D. Indeed, this approach has its limitations and cannot guarantee anatomically accurate bone reconstruction. In the proposed system, fracture reduction is performed interactively in 3D. The user identifies corresponding features on bone fragments and the system computes a transformation that aligns these features automatically. Afterwards, the user may observe the result and make corrections if necessary, as shown in Fig. 3.

C. Specification of guide curve

The user selects a set of points on the mesh fragments that identifies the desired location and placement of the plate. Then, a NURBS curve interpolating the user selected points on the surface of the bone is computed. In Fig. 4, a single mesh representing the fractured bone is shown for the sake of illustration of the concept. In general, segments of guide curve path may be computed on the independent bone fragments after reduction. The resulting curve may have wiggles with high curvature that cause unnatural and undesirable deformations to the plate when axial deformation is applied. So the curve is first smoothened using a Laplacian technique [3], which acts as a low pass filter thereby reducing undesirable high curvature features. Fig. 4 shows a region of the guide curve with a large number of wiggles (red curve) that is smoothened (black curve) to obtain a better axial deformation curve.

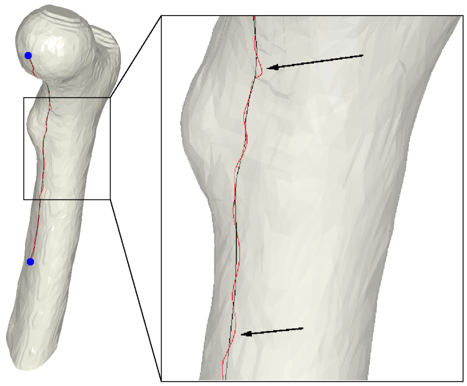


Fig. 4. Blue points indicate user specified location to place plate. Guide curve is smoothed to reduce undesirable wiggles. The original curve is shown in red and the smoothened curve is shown in black. Arrows indicate wiggles in the original curve.

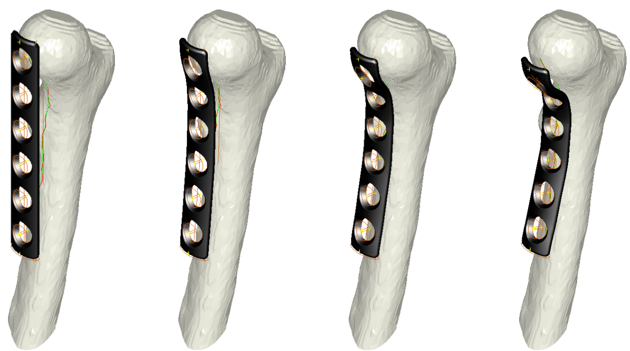


Fig. 5. Arc length based interpolation of guide curve for plate adaptation using smooth deformation.

D. Initialization of plate CAD model

CAD models can contain curve and surface geometry defined by linear (line segments, planes) and quadric (circular arcs, ellipses, cylinders, spheres) analytic representations in addition to the more general NURBS representation. Low degree analytic representations are not sufficient to represent the deformed geometry of the adapted plate. For example, a deformed cylinder can no longer be represented by the original quadric representation, and more flexible representation is required. Therefore, all curves and surfaces in the original CAD model are converted to higher order NURBS using standard techniques [4], [7]. The NURBS curve and surface representations may not have sufficient degrees of freedom (i.e., control points) to achieve the desired adapted CAD model. Additional degrees of freedom are added in order to obtain smooth deformations especially in highly curved regions. The number of degrees of freedom added is a user-specified factor of the maximum curvature of the deformation guide curve. Efficient algorithms for increasing degrees of freedom are presented in [4].

E. Adaptation of plate CAD model

The flexible NURBS model is placed in the desired region using the user selected points on the bone mesh. Adaptation is performed using the axial deformation technique discussed in Section II. The model axis is set as the initial curve and the guide curve is set as the final curve. The control points of all the curves and surfaces of the CAD model are transformed using the axial deformation technique. The transformed control points define the geometry of the deformed plate CAD model. Since the final guide curve is smooth, the deformed plate model is also smooth.

The deformed CAD model should not penetrate the bone surface. In the current system, the guide curve is interpolated between the initial axis and the final curve on the bone surface. The plate model is deformed at every step using the interpolated curve and tested for collisions with the bone mesh. If there is a collision, the deformation stops. The user can reset the guide curve and perform the adaptation, if required.

Interpolation of the guide curve is performed using an arc-length parameterization based method that ensures smooth interpolation of curve length [5]. Fig. 5 shows several steps of the deformation applied to the interpolated guide curves. The final adapted plate model is represented as a NURBS based CAD model. This model can be directly manufactured using traditional CNC machines.

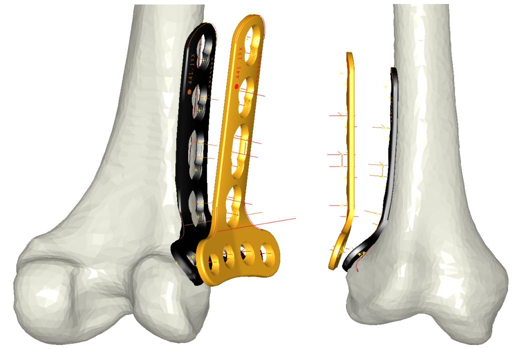


Fig. 6. Two views of customized plate on distal femur bone. Original plate is shown in gold and customized plate is shown in black.

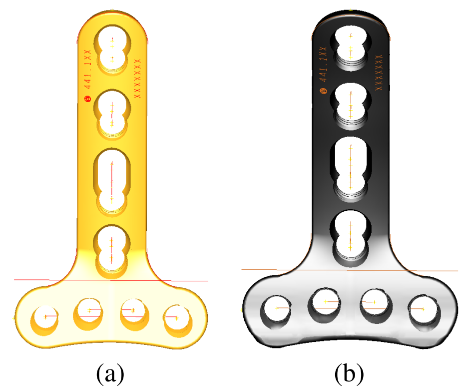


Fig. 7. (a) original plate for distal femur (b) customized plate.

IV. RESULTS

This section presents results on applying the proposed technique on more complex fixation plates. Fig. 6 and Fig. 7 show a customized plate for the distal region of the femur bone. This plate model contains more complex geometric

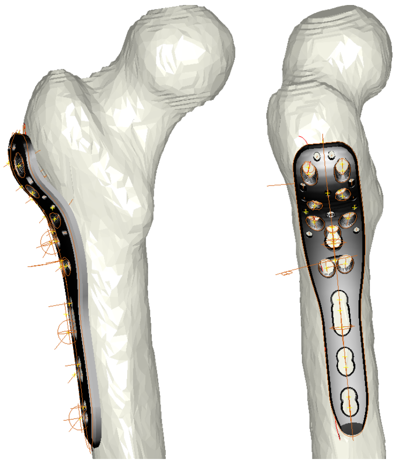


Fig. 8. Two views of customized plate on proximal femur bone.

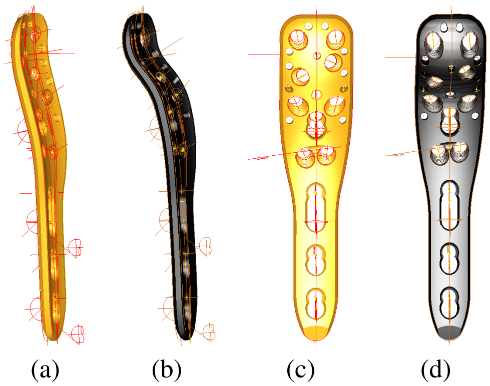


Fig. 9. Two views of original plate in gold ((a) and (c)); and two views of customized plate in black ((b) and (d)).

features such as threaded holes as compared to the plate shown in Fig. 1. Fig. 8 and Fig. 9 show the results of applying the proposed customization technique on a model with even more complex geometric features. Fig. 10 shows a polygonal mesh representation of the CAD model for comparison. A mesh representation requires very fine tessellation to accurately represent complex geometric features of the original CAD model. With the proposed approach, the accuracy and smoothness of the customized model is comparable to the original CAD model as shown in Fig. 7 and Fig. 9. These examples illustrate efficiency of the proposed approach in handling very complex geometries.

V. CONCLUSIONS AND FUTURE WORK

A. Conclusions

This paper demonstrates the feasibility and benefits of using native parametric CAD models directly in interactive preoperative planning tools. A new method for performing fracture plate adaptation to create customized plates is proposed. Digital models of plates are typically available as CAD models that contain smooth analytic geometry representations including NURBS. Existing methods for plate adaptation use tessellated polygonal models obtained by sampling of smooth CAD geometry. Such methods are computationally expensive due to fine tessellation required for higher accuracy and smoothness, and require reverse engineering to recreate CAD models of customized plates for manufacturing. The proposed method avoids these issues by directly modifying NURBS geometry to create custom CAD plates that conform to the desired region of the bone surface of patients. The resulting CAD models are smooth and can be directly used for manufacturing patient-specific customized plates.

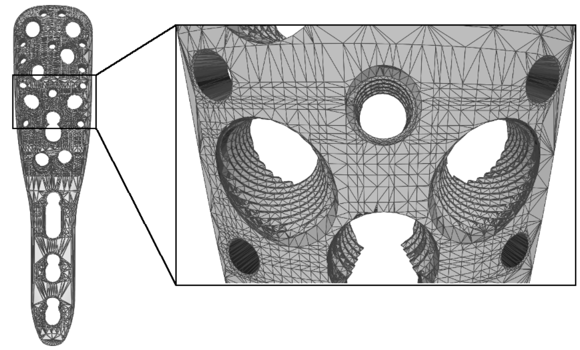


Fig. 10. Polygonal mesh approximation of CAD model. Very fine tessellation is required to accurately capture complex geometry.

B. Future Work

There are several avenues for future work to extend the ideas presented in this paper. Other types of fixation plates may require more general spatial deformation techniques defined by a set of guide curves or surfaces. We are currently investigating more general adaptation strategies as well as intuitive interaction techniques for reduction of bone fragments and initial placement of other types of plates on various types of bones.

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