

Design and application of tailor-made plates for treating fractures in small animals

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Abstract—We propose here the use of a computer-aided design (CAD) system in the treatment of fractures in small animals. During surgical planning, the veterinarian sketches a simple plate referring to computed tomography images. A CAD operator then models the plate by polygonal approximation (triangulation) of the surface of the bone region. After importing the approximated shape into the CAD system as a triangulation mesh, a detailed design of the plate is then prepared in the CAD system by referring to the abovementioned sketch. The plate can be designed to match the bone surface since the plate surface follows the curvature of the surface of the exported triangulation mesh. Furthermore, the bone shape and plate are eventually converted into polygon shapes, and a structural model identical to the fractured part of the bone can be reproduced using a 3D printer, allowing for alignment to be performed at full scale. In this study, we examined the applicability of the proposed system by designing the most appropriately shaped plate for bone fracture therapy in small dogs brought to a veterinary clinic for treatment.

Keywords: Tailor-made plates; 3D dimensional image; 3D CAD system; Fracture; 3D Printer; Casting

I. INTRODUCTION

In veterinary clinics, treatment of fractures that require plating in small animals involves cutting a long flat plate to the necessary length and affixing it with appropriate screws while following the curvature of the bone surface (Fig. 1). The plate is made based on measurements taken from X-ray images (computed radiography images) and computed tomography (CT) images. However, the process of cutting and bending the plate either pre- or intraoperatively imposes burden on veterinarians and takes considerable time. Furthermore, for non-trivial fracture sites (e.g., in the case of comminuted fracture), during surgery it is extremely difficult to prepare a plate that follows the bone shape. Therefore, here we propose a system that enables veterinarians to use computer-aided design (CAD) with CT images taken preoperatively to design and manufacture appropriately shaped plates for fixing the fracture.

A 3D rendered image of the fracture site can be obtained from CT multi-slice images. Initially, the veterinarian extracts the region corresponding to the bone from the 3D image by applying image processing, after which a simple plate is designed by drawing a sketch while referring to the displayed

image of the bone. The approximate values for the length and width of the plate, the number and locations of screw holes, and the curvature of the plate are estimated at this stage (Fig. 2). In example (A) in Fig.2, the image on the left shows the shape of the fractured bone and the image on the right shows sketches drawn on top of mirror images of the corresponding bone on the unaffected side. Example (B) shows the shape of the plate together with the screw holes and directions of the screws for the frontal and lateral images.

A CAD operator then models the plate, using polygonal approximation (triangulation) of the surface of the bone region. After importing the approximated shape into the CAD system as a triangulation mesh, a detailed design of the plate is prepared in the CAD system by referring to the abovementioned sketch. Particularly in cases of simple bone fracture in limbs, the fracture site is extracted as separate partial images. These partial images are then joined by computer and the restored bone shape is exported as a triangulation mesh. As a result, the plate can be designed to match the bone surface since the plate surface follows the curvature of the surface of the exported triangulation mesh. When the bone fracture is complex, however, because of the bilateral symmetry of the body, mirror transformation of images of the corresponding bone on the unaffected side can be used. Then after constructing the virtual bone shape, the plate can be designed to match it.

Furthermore, in the proposed system the bone shape and plate are eventually converted into polygon shapes. A structural model identical to the fractured part of the bone can then be reproduced using a 3D printer, allowing for alignment to be performed at full scale. In this study, we examined the applicability of the proposed system by designing the most appropriately shaped plate for bone fracture therapy in small dogs brought to a veterinary clinic for treatment.

The rest of this paper is structured as follows. Section 2 outlines the system structure and the design process, Section 3 presents an example of application and an evaluation of the system. Section 4 provides concluding remarks.

II. OUTLINE OF THE SYSTEM CONSTRUCTION AND DESIGN PROCESS

Figure 3 shows the overall process flow in the proposed design system. The obtained multislice CT images are

provided in DICOM (Digital Image Communication Modality) format, where location information at the time of acquisition is saved in each slice image. A high-resolution 3D image can be obtained when the gap between slice images is sufficiently narrow.

The 3D image prepared from the multislice images is divided into bone regions and other regions by using the image processing technique of binarization. Since commercial CAD systems cannot manipulate 3D images directly, the binarized bone region is converted into an isosurface of the bone surface (triangulation mesh) through isosurface processing. At this stage, the bone isosurface is not defined as a solid model with strict 3D geometry. Since the isosurface is extracted from CT images of a biological object, if the shape is complex, it suffers from various deficiencies, irregularities, and partitioning (e.g., with multiple insular regions). Data reduction and alignment is therefore needed to convert it into a CAD model.



Fig. 1 Affixing a conventional plate



Fig. 2 Example sketch prepared by a veterinarian using the proposed design system

In the proposed system, if the generated isosurface is simple and allows for straightforward conversion into a solid model, then such conversion is performed. However, if conversion of the entire object is difficult to perform or it would require a considerable amount of time, a surface (free curve) approximating the triangulated isosurface is prepared. The plate is designed using the resulting approximation surface. When conversion to a solid model is possible, various geometric operations and computer simulations can be performed with the CAD system. For example, the simulation capabilities of computer-aided engineering (CAE) systems can be used when more detailed evaluations are necessary, such as determining the degree of conformance between the bone surface and mounting surface of the plate or performing stress analysis. Furthermore, full-scale models of the designed plate and fractured bone can be manufactured with a 3D printer using resin or gypsum. This allows for final inspection of the shape, screw hole locations, mounting surface with respect to

the bone shape, and other parameters. The final metal plate is prepared by molding, cutting, electron-beam melting (EBM), or other manufacturing method.

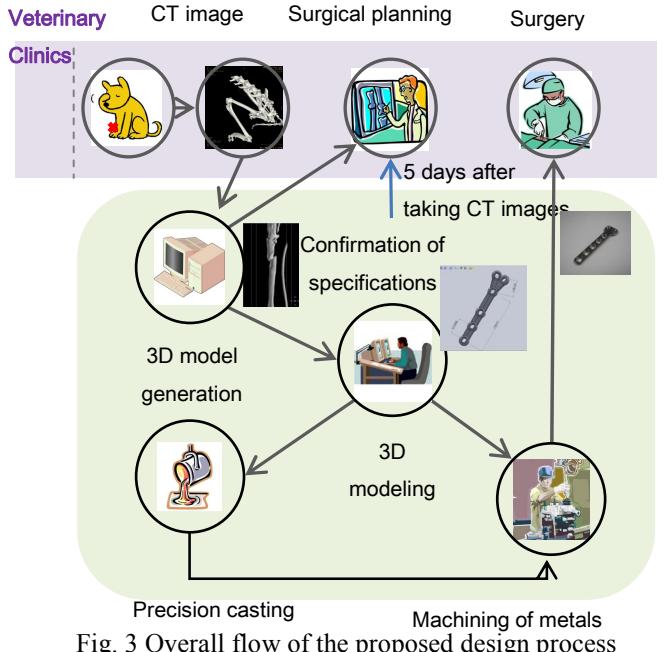


Fig. 3 Overall flow of the proposed design process

III. PROCESS FLOW OF GENERATING TAILER-MADE TEMPLATES

Reproduction of bone surface shape from CT images

The acquired CT images are divided into bone regions (fractured and healthy bone) and other regions by binarization. The binarization threshold values are taken on the basis of the Hounsfield units, which are around 300–500, and the values are eventually configured interactively using a histogram as a reference. As the threshold values differ for regions corresponding to cortical and cancellous bone tissue and cartilage, values corresponding to cortical bone tissue are selected in order to represent the entire bone surface. Automatic noise reduction and interactive cleaning are conducted if small amounts of noise (salt-and-pepper noise), disjoint insular areas, artificial objects, or other irregularities are present after binarization.

Clipping the 3D image and generating a spliced image by cross-section alignment

If cross sections can be sufficiently well approximated as planes, 3D images are cut along the cross-sectional planes, and a state close to that of the original healthy bone can be reproduced by connecting disjoint 3D images at cross-sectional planes [1]. A software tool that interactively determines such cross-sectional planes and connects corresponding planes at sites of clipping was developed in order to perform all of these operations. The software tool is referred to as JointVision in this paper. JointVision is capable of generating 3D images from slices, displaying, processing,

and clipping 3D images, as well as connecting multiple 3D images. Each operation is performed interactively by the user while the 3D images are displayed (Fig. 4). It is an OpenGL [2] application for Windows. A high-speed volume rendering system is also utilized that combines 3D texture compression and parallel programming techniques for rendering multiple high-resolution 3D images obtained by medical or industrial CT [3, 4].

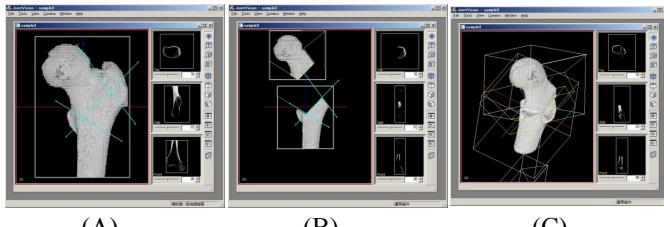


Fig. 4 The newly developed software tool for (A) selecting the cross-sectional plane, (B) clipping the 3D image, and (C) connecting two 3D images.

Preparing a mock image of the healthy bone through mirror transformation

For complex fractures, when the original state is difficult to determine, an effective method involving horizontal flipping (mirror transformation) can be applied to the healthy bone on the unaffected side to construct a bone shape similar to the original shape of the fractured bone. Mirror transformation can be performed either in 3D image space or in 3D geometrical space in CAD. We describe here mirror transformation in 3D image space to illustrate the shaping of the plate wanted by the veterinarian in image space, which is more realistically the method that would be used in veterinarian clinics. With respect to the transformed 3D image, after volume rendering and isosurface processing, an outline image (sketch) of the plate is drawn with the paint function on top of a screenshot of the image.

Generating the bone surface shape from the imaged bone surface

In order to construct a bone surface model (triangulation model) from the extracted bone region (3D image), isosurface processing is performed using the marching cubes method. Since a large amount of triangulation data is generated when applying isosurface processing to high-resolution CT images, data reduction processing is also performed while preserving the shape characteristics with the quadric error method[5]. The generated triangulation model is recorded as a solid model by using a universal CAD system. The CAD/CAM/CAE systems used in this study were CATIA Version 5 (e.g., for analyzing the stress between the designed plate and bone surface) and SolidWorks 2011 for simple modeling.

Designing the plate

To make the plate design as effective as possible, a commonly used plate pattern is pre-designed and used at first, and the user inputs the necessary number of screw holes as a

parameter. The plate type (standard shape) can be prepared according to user requirements. Although there are three types of currently available patterns—a type with plain ends, a type where the angle of one end is changed, and a type with two screw holes only at one end—other plate types can be added as necessary (Fig. 5). Furthermore, the number and locations of screw holes, plate length, curvature, and other characteristics are parameterized for each plate type, and the user is provided with a form in which the tabulated parameters can be changed. A plate is generated automatically each time the parameters are altered. Thus, the process of designing the plate with the most appropriate shape for fixing to the bone surface is almost completely automatic.

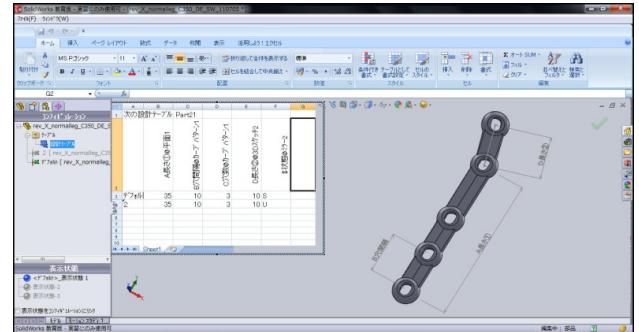


Fig. 5 Parameter table and generated plate in SolidWorks 2011.

Figure 6 shows the surface regions on the repaired bone surface specified by the user with painting. Figure 7 shows B-spline surface generation on the bone surface. By adjusting the curvature of the plate on the bone surface, an optimized tailor-made plate is designed. Figure 8 shows an example of a tailor-made plate. Figure 9 shows the cross-sectional image of both the bone surface and the tailor-made plate.



Fig. 6 Repaired bone and painted regions

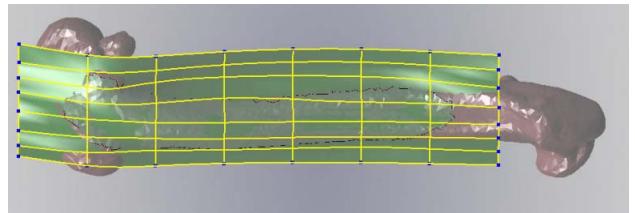


Fig. 7 Surface generation of bone triangles

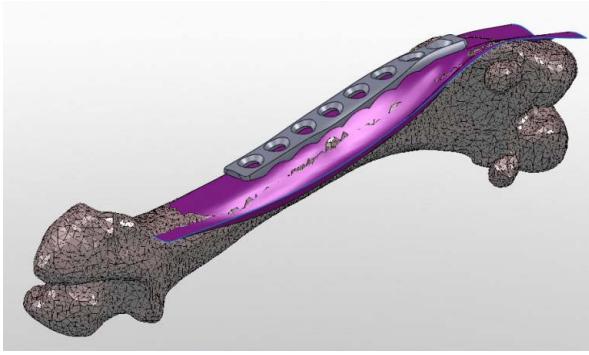


Fig. 8 Designing a tailor-made plate for the surface

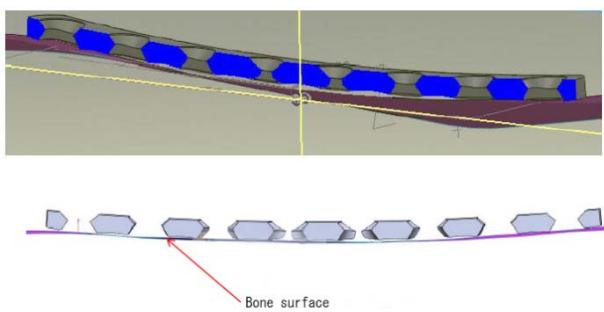


Fig. 9 Cross-sectional plane image of the bone surface and tailor-made plate

IV. EVALUATION

After designing the plate, the materials and the processing and manufacturing method for the actual plate and screws can be chosen from several options. In this paper, we introduce samples manufactured by molding suitable materials, which include stainless steel, titanium alloy and cobalt alloy.

In the example shown in Fig. 8, the most appropriate plates for the thighbones of beagles used in the experiment were designed using CT images and then the thighbones and plates were manufactured with a 3D printer. In the upper and lower rows, the number of screw holes and curvature in the vertical direction was different for different beagles, and each plate was designed to match the surface of the corresponding bone. Since the extracted bone shape model is represented as a collection of triangles, a curved surface approximating this triangulated surface was prepared using the CAD system described above. The curvature of the resulting curved surface was subsequently used for designing the plate. Gaps were left between the screw holes to ensure that blood flow was not obstructed. Figures 10 and 11 show examples of models of tailor-made plates and bones made with a 3D printer.

We utilized a vacuum-pressure casting machine (Heracast iQ, Heraeus Ltd.) (Fig. 12). This machine has high-quality and reliable casting features, and is often used in dental fields. The metal we used in casting was a composite material from cobalt-chromium-molybdenum (Co-Cr-Mo) alloy [6, 7], developed at the Institute for Materials Research Laboratory,

Tohoku University. Figure 13 shows how the mold for casting was created.



Fig. 10 Tailor-made plates manufactured with a 3D printer

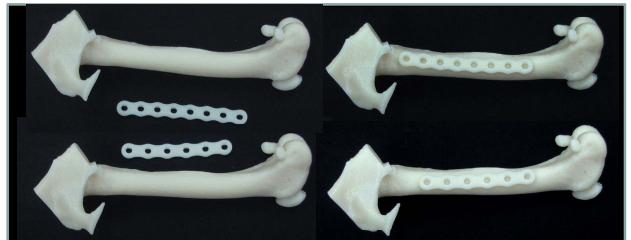


Fig. 11 Examples of structures manufactured to correspond with the bones



Fig. 12 Vacuum-pressure casting machine



Fig. 13 Molding process of a tailor-made plate

Figure 14 shows the actual metal plate molded with the casting machine.

We used five experimental animals in this study. From CT images taken of the animals, we generated isosurfaces of the thigh bone, and designed five tailor-made plates on SolidWorks 2011. The process of designing the tailor-made plate took around thirty minutes for each animal. We made a total of ten metal plates, five made from the composite

material Co-Cr-Mo alloy with zirconium (Zr) and the other five plates without Zr. The plastic plate was generated in around one hour using a Dimension 3D printer (SST1200es, Stratasys, Inc., Waltham, MA. Casting and polishing for each metal plate took two to three hours. Figure 15 shows X-ray images of Co-Cr-Mo alloy plate after the surgery. Finally, the five plates with Zr and the five plates without Zr were fixed to the thighbones of the five experimental animals.

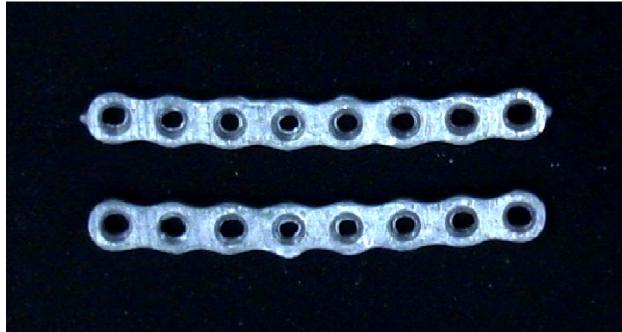


Fig. 14 Manufactured plates for fixing to bone in the experimental animals



Fig. 15 Plates fixed to the thighbones of the experimental animals

V. CONCLUSION

In contrast to conventional techniques, using the proposed system the veterinarian manufactures a tailor-made plate preoperatively by referring to a sketch prepared from CT images. This drastically reduces the burden on the veterinarian during surgery. Planar plates are rather difficult to cut and bend during surgery when the fracture is complex or the curvature of the mounting surface varies considerably. Therefore, since tailor-made plates are designed, processed, and manufactured by taking into account individual differences and the specifics of the particular case, during surgery the veterinarian can focus on fixing the plate to the fractured bone, which reduces operation time. Furthermore, preoperative training and rigorous inspection can be conducted using bone models manufactured with 3D printers or similar technology.

In the case of a simple fracture, CT images are divided into partial images at the fractured bone surface, and the original state can be reproduced by moving and rotating each image. However, a method that has proven to be effective when the original state is difficult to determine due to the complexity of the fracture involves horizontal flipping (mirror transformation) of the images of the healthy bone on the unaffected side and preparing a bone shape close to that of the original fractured bone. Mirror transformation also aids veterinarians in imagining the shape of the healthy bone. Although the most time-consuming part in the proposed approach is the manufacturing of the actual plate, small plates (up to 20 cm in length) can be molded within several hours with highly precise molding techniques used in dental clinics. , Five-axis processing machines and cutting machines are effective when larger plates are needed.

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REFERENCES

- [1] I. Fujishiro, M. Okutomi, et al., "Visual Information Processing - Introduction of CG/Image Processing ", CG-ARTS Association, pp. 115-116, 2007.
- [2] Open GL Programming Guide Fifth Edition – The Official Guide to Learning OpenGL", Version 2, Addison-Wesley Pearson Education, 2006.
- [3] A. Doi, T. Takahashi, T. Mawatari, and S. Mega, "Development of a volume rendering system using 3D texture compression techniques on general-purpose personal computers", Proc. of IEEE iCAST 2011, Dalian/China, 2011.
- [4] AMD Corp., "3D (Volume) texturing and Volume Texture compression", ["http://developer.amd.com/gpu/radeon/archives/radeon_sdk_introduction/"](http://developer.amd.com/gpu/radeon/archives/radeon_sdk_introduction/), ATI Radeon SDK Introduction Archive | AMD Developer Central", 2010.
- [5] M. Garland and P. Heckbert, "Surface simplification using quadric error metrics", Proc. of SIGGRAPH '97, pp. 209-216, 1997.
- [6] E. Onodera, Y. Li, H. Matsumoto, A. Chiba, "Intelligent hot forging process of artificial hip joint made of Ni-free Co-29Cr-6Mo-0.12N alloy ...", Steel Research International, Vol. 81, pp. 362-365, 2010.
- [7] S. Kurosu, H. Matsumoto, A. Chiba, C. Landron, D. Fabregue, E. Maire, "The damage process in a biomedical Co-29Cr-6Mo-0.14N alloy analyzed by X-ray tomography and electron backscattered diffraction", SCRIPTA MATERIALIA, Vol. 64, No. 5, pp. 367-370, 2011.