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Virtual haptic system for intuitive planning of bone fixation plate placement

Kup-Sze Choi [a,*], Beat Schmutz [b], Xue-Jian He [a], Wing-Leung Chan [c], Michael Schuetz [d]

[a] *Centre for Smart Health, School of Nursing, Hong Kong Polytechnic University, Hong Kong*
[b] *Institute of Health and Biomedical Innovation, Queensland University of Technology, Australia*
[c] *Department of Orthopaedics and Traumatology, Hong Kong Baptist Hospital, Hong Kong*
[d] *Centre for Musculoskeletal Surgery, University Clinic Charité, Germany*

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ABSTRACT

Placement of pre-contoured fixation plate is a common treatment for bone fracture. Fitting of fixation plates on fractured bone can be preoperatively planned and evaluated in 3D virtual environment using virtual reality technology. However, conventional systems usually employ 2D mouse and virtual trackball as the user interface, which makes the process inconvenient and inefficient. In the paper, a preoperative planning system equipped with 3D haptic user interface is proposed to allow users to manipulate the virtual fixation plate intuitively to determine the optimal position for placement on distal medial tibia. The system provides interactive feedback forces and visual guidance based on the geometric requirements. Creation of 3D models from medical imaging data, collision detection, dynamics simulation and haptic rendering are discussed. The system was evaluated by 22 subjects. Results show that the time to achieve optimal placement using the proposed system was shorter than that by using 2D mouse and virtual trackball, and the satisfaction rating was also higher. The system shows potential to facilitate the process of fitting fixation plates on fractured bones as well as interactive fixation plate design.

1. Introduction

Anatomically pre-contoured plates are commonly used in orthopaedic surgery for internal fixation of bone fracture. The plates are designed to serve as templates to fit the anatomy of the majority of patients and minimize the need of plate bending [1]. A common approach of plate design is to make reference to bone specimens obtained from cadavers, which are of limited availability and may not be representative for different bone morphology [2]. To facilitate the design, virtual reality (VR) systems have been made available [3] where the bone models reconstructed using morphological data of bones acquired by medical imaging modalities like computed tomography (CT) enable the design of more adaptable pre-contoured fixation plates. Besides, the plate fitting process can be performed more flexibly in 3D virtual environment. Nevertheless, as morphological difference of bone exists in people of different races age or gender, it is practically difficult to design a single set of standard plates for the whole population. As a result, preoperative evaluation of the fitness between the pre-contoured plates and the anatomy of specific patients is needed in order to choose the best plate that is most suitable for the fixation of the fractured bone.

In VR-based fixation plate placement system, a plate is manipulated to fit the virtual bone model reconstructed from medical imaging data using the virtual trackball technique [4], where a 2D computer mouse is employed to emulate the manoeuvres of a physical trackball. While this is a common technique to manipulate 3D objects using 2D user interface, it is cumbersome and time-consuming since the plate-bone fitting process require fine movements and high dexterity. To this end, 3D user interface device with force feedback is proposed in this study to facilitate the process by improving the usability of the virtual placement systems and thus the efficiency of fit optimization. Related studies have shown that using 3D input devices can increase task completion time by 36% and without loss of accuracy when compared to virtual trackball [5]. Rendering of haptic force feedback in the virtual fit optimization process is also expected to raise the level of intuitiveness during manual manipulations. In fact, the plate fitting process concerned here can be considered as industrial product design processes that require the assembly of multiple parts, where VR technology and haptic feedback have been employed to realise virtual assembly. In reality, forces resulting from collisions due to geometrical constraints of physical parts provide natural and intuitive haptic feedback to guide the assembly process [6]. If the process is simulated using VR with visual and audio feedback only, the lack of interaction forces would degrade the level of simulated realism and the virtual assembly tasks would be difficult to proceed and prone to errors [7]. On the contrary, the efficiency of virtual tasks is

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[*] Corresponding author.
E-mail address: hskschoi@polyu.edu.hk (K.-S. Choi).

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improved significantly when users can make use of their haptic sensation to determine the relative positions of the component parts and the physical constraints, thereby relieving cognitive load due to heavy reliance on visual perception [8].

However, integrating haptic device into VR-based fixation plate fitting system is non-trivial. First, as the size of volumetric data acquired by medical scanning of the bones are very large, real-time collision detection of 3D bone models reconstructed directly using the data is computationally prohibitive for real-time performance. The situation is further exacerbated by the high data update required, as high as of 1 kHz, for the rendering of smooth haptic forces in real time. Second, conventional haptic rendering approaches, e.g. the god-object [9] and proxy [10] methods, are only applicable for interactions with 3 degrees-of-freedom (dof). In the proposed fixation plate placement system, a simulation framework is developed to enable stable and efficient collision involving 6-dof position/orientation input and 3-dof force output, realised by using 3D haptic user interface device.

The paper specifically focuses on improving the user interface in conventional systems that use 2D mouse and the virtual trackball metaphor to manipulate the fixation plate and determine the optimal placement on fractured bone. Thus, the aim here is to develop an improved version of the medical application using technology, instead of developing new collision detection or haptic technology. However, the former involves non-trivial implementation issues that need to be addressed in order to practically realise the proposed system with the technologies, which are discussed in detail in the paper. Besides, the system is also tested by human subjects to evaluate the system performance and usability.

The rest of the paper is as follows. Section 2 reviews the work related to the present study. Section 3 presents the details of the proposed approach, including the criteria of plate-bone fitting, 3D model construction, collision detection and response, and haptic rendering. Sections 4 and 5 describe the details of the implementation and the experiments conducted respectively. Section 6 discusses the findings from the study and the issues. Conclusions and future work are presented in the last section.

2. Related work

In this section, the assessment of the fitness of fixation plate placement is first discussed, followed by a review of haptic-based virtual assembly systems that is relevant to the design of the proposed virtual fixation plate placement simulator.

2.1. Fit assessment of fixation plates

Given the importance of the fitness of pre-contoured fixation plate placement, researches have been conducted to assess how well the plates can conform to bone morphology. In a study attempting to evaluate the fitness of a set of proximal tibia plates [2], the optimal positions of the plates on tibia samples are determined physically and the relative positions obtained are digitized for quantitative evaluation of the accuracy. This is a reverse engineering approach and the manual fit assessment process is time-consuming and error-prone. Besides, the assessment involves only a finite set of bones which cannot adequately represent the morphological variations across different populations. To facilitate fit assessment, computer-based systems are then developed to automate the process [11]. Fitting is performed in virtual environment using 3D virtual bone models reconstructed from medical imaging data acquired by CT scans. For example, a semi-automated system is developed to allow users to position the plates using virtual trackball and evaluate the fitness of the distal medial tibia plates [1,3,11,12]. This method is therefore not limited to cadaver or prototype bones but any other bone samples as long as the medical image data are available. However, when a large amount of bone samples is of interest, the manual fitting process, despite being conducted in virtual environment, remains time-consuming. The assessment is also dependent on the skillfulness of the operators [11]. Fully automated fit assessment is thus investigated. For example, the fitness of proximal tibia plates is automatically evaluated using statistical shape analysis [13]. As the average distance between the plates and underlying bone surface is used as the only criterion, the outcomes may not be the most optimal position [11]. Also, the agreement between the outcomes of the statistical model and the bone morphology is unclear and needs to be verified.

2.2. Virtual assembly

VR technology has long been applied to facilitate the design, analysis and evaluation of the assembly of mechanical parts. These virtual assembly systems are analogous to the virtual fixation plate placement system concerned in this study. Operators of the virtual assembly systems manipulate human-machine user interface devices to move the component parts around and assemble them in virtual environment. The virtual parts can respond to the actions of the operators through multiple modalities, visual, audio or haptic. Virtual assembly systems can be classified into constraint-based and physics-based systems [14]. For the former systems, geometric constraints due to the shape and dimension of the parts govern the possible manoeuvres during the process, while for the latter, dynamics of the parts is simulated based on physical laws in addition. The forces and torques during the interactions are computed to render haptic feedback when collisions are detected, so that undesirable interpenetrations of the virtual parts can be avoided in a more intuitive manner. The level of virtual realism of physics-based virtual assembly systems are therefore more superior as the operators can make use of their haptic sensation in addition to the visual and audio perception [14]. Physics-based simulation with haptic feedback is thus proposed for the virtual fixation plate placement system in this study.

A number of physics-based virtual assembly systems with haptic user interface are briefly discussed below. In the Haptic Integrated Disassembly and Reassembly Analysis (HIDRA) system [15], the thumb and index fingers of the operator are attached respectively to two haptic devices to provide haptic feedback during the processes. The software package V-Clip [16] is used for collision detection, where all the object models are first decomposed into convex components [17]. The collision responses are simulated based on impulse-based dynamics [18]. In the virtual assembly system Haptic Assembly Test bed (HAT) [19], a pair of haptic devices are adopted for the simulation of peg-and-hole assembly, which is used to compare the performance of operators in conducting the virtual and real task. Collision detection and dynamics simulation of the system are implemented using the real-time physics engine PhysX of the NVidia Corporation. Unlike the two previous systems where 6-dof haptic devices are used, the Virtual Environment for Design and Assembly Planning (VEDAP-II) system [20] is equipped with more sophisticated haptic devices, the CyberForce system of the Immersion Corporation, taking hand kinematics into account in the simulation. In the system, dynamics simulation and haptic rendering are handled by two separate models which are linked through virtual coupling [21].

Despite the high simulation fidelity offered in physics-based virtual assembly, it is challenging to deal with applications with more stringent requirement on precision where the fitting clearance is very small. For example, in the physics-based System for Haptic Assembly and Realistic Prototyping (SHARP) system, voxel-based approximations are used for virtual assembly [22]. While the precision can be increased simply by reducing the voxel size of the object models, it can lead to high computational cost and affects system stability. A hybrid approach combining physics-based and constraint-based methods is thus suggested to tackle this issue, e.g. using B-rep surface representations for developing fast and accurate collision algorithms. Adopting this idea, a virtual assembly called the Haptic Assembly and Manufacturing System (HAMS) [23] is developed where the states of motion of the manipulated objects are governed by physics simulation engines only when they are manipulated freely in virtual environment. Constraint-based simulation is activated when the objects are in close proximity to other parts.

3. The fixation plate placement system

An overview of the proposed system is first outlined in this section. The fitness criteria for fixation plate placement, the techniques used for reconstructing the 3D models of the plates and bones, i.e., convex decomposition and model decimation, the collision detection and response algorithms, and the haptic rendering algorithm are then discussed in detail.

3.1. System overview

In the proposed system, a plate is manoeuvred around the bone to locate the best fit position in the virtual environment using a haptic device. The framework of the system is shown in Fig. 1. The 3D models of the plate and bone, pre-processed by decimation and convex decomposition, are first imported into the system. At the beginning of the fitting process, user controls a virtual cursor by manipulating the stylus of the haptic device and moves the cursor towards the plate to hold it. Virtual coupling is employed to ensure stable control of the plate and smooth haptic rendering. The algorithm for detecting plate-bone collisions is also activated to generate appropriate responses and feedback forces in real time. The plate is then manipulated around the bone, which is fixed in the virtual environment, to locate the best fit position. The system checks if the fit criteria are satisfied on the fly. It also records performance data, including task completion time and fitting errors. During the fitting process, visual feedbacks are also provided interactively via the graphical user interface, as shown in Fig. 2. Based on the advice of orthopaedic surgeons, the virtual environment is rendered from three angles, i.e., the top view, perspective view and axial view, which provides multi-view information to facilitate subtle alignment and visual judgement, and to preclude the effect of occlusion.

3.2. Fit criteria

The four fit criteria defined in Refs. [1,3] are adopted in this study. They are spatial constraints set to meet the clinical requirements and to accommodate the morphological differences of bones. Refer to Fig. 3, the criteria are:

- Criterion #1: the plate-bone distance is less than 4 mm within 20 mm from the proximal tip of the plate;
- Criterion #2: the plate-bone angle is less than 10° measured at a distance of 80 mm from the proximal end of the plate;
- Criterion #3: the plate-bone distance is less than 6 mm at the middle third of the plate;
- Criterion #4: the plate-bone distance of the five points, three at the distal tip of the plate and the two most proximal points at the transition of meta-to diaphysis, is less than 2 mm.

3.3. Convex decomposition

The plate model is decomposed into convex components to facilitate collision detection. It is also more efficient to simulate the dynamics using convex components that the original concave components [24]. However, exact convex decomposition of complex object is usually computationally inefficient and produces a large number of mesh components [25]. Several approximate convex decomposition (ACD) methods have thus been proposed [26,27]. In general, ACD algorithms iteratively divides the mesh using the divide-and-conquer strategy until the concavity of each sub-mesh is lower than a threshold. In the paper, the Hierarchical Approximate Convex Decomposition (HACD) algorithm is adopted [26], where hierarchical segmentation of a triangular mesh is conducted by applying a series of topological decimation operations to its dual graph. The decomposition produces a smaller number of convex components and better retains the structure of the model.

Refer to Fig. 4, for a point Q on the mesh S, the concavity $C(S)$ of a 3D mesh S is

$$C(S) = arg^{max}_{Q\in S}||Q - P(Q)||, \tag{1}$$

where $P(Q)$ is the projection of Q to the convex hull $CH(S)$ along the direction N at point Q, and $||\cdot||$ is the Euclidean norm. The accuracy of the decomposed model is evaluated by the maximum concavity C_m [26]. To evaluate the approximation error, the metric Hausdorff distance $d_H(X, Y)$ is adopted to calculate the approximation error between the original mesh X and the decomposed mesh Y as follows,

$$d_H(X,\ Y) = \max\left(\underset{x\in X}{sup}\ \underset{y\in Y}{inf}\|x-y\|,\ \underset{y\in Y}{sup}\ \underset{x\in X}{inf}\|x-y\|\right), \tag{2}$$

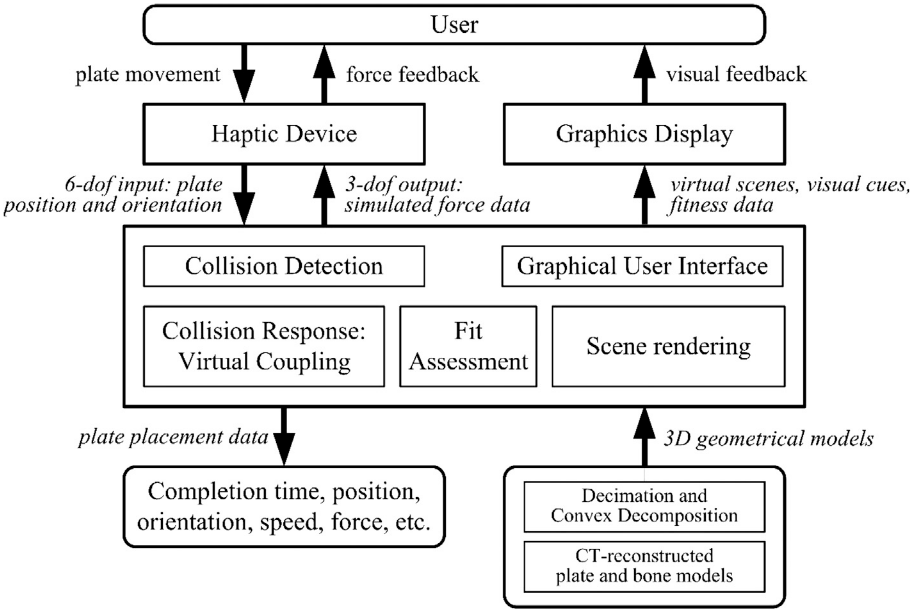


Fig. 1. Schematic diagram showing the system framework.

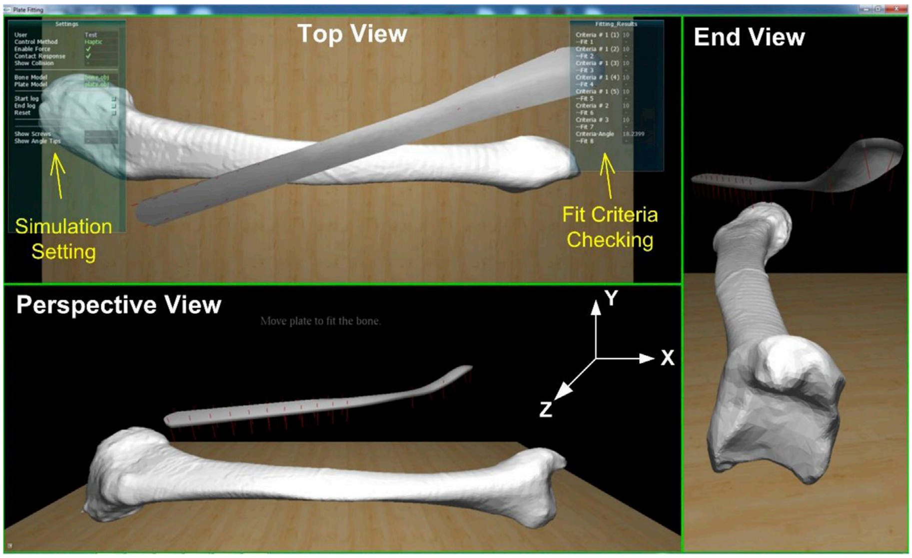


Plate Fitting

Settings

User Test
Control Method Haptic
Enable Force ✓
Contact Response ✓
Show Collision -
Bone Model bone.obj
Plate Model plate.obj
Start log
End log
Reset
Show Screws -
Show Angle Tips -

Fitting_Results

Criteria # 1 (1) 10
--Fit 1 -
Criteria # 1 (2) 10
--Fit 2 -
Criteria # 1 (3) 10
--Fit 3 -
Criteria # 1 (4) 10
--Fit 4 -
Criteria # 1 (5) 10
--Fit 5 -
Criteria # 2 10
--Fit 6 -
Criteria # 3 10
--Fit 7 -
Criteria-Angle 18.2399
--Fit 8 -

Move plate to fit the bone.

Fig. 2. Screenshot of the graphical user interface.

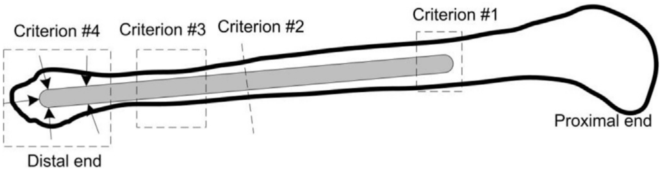


Fig. 3. Placement fit criteria.

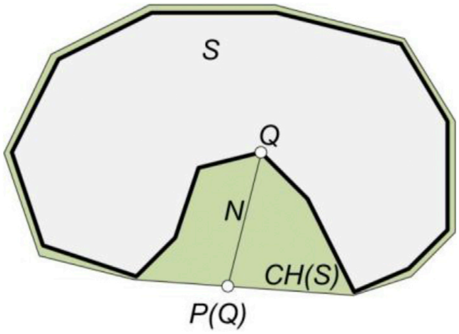


Fig. 4. Concavity of a 3D mesh S.

where sup is the supremum and inf is the infimum. As illustrated in Table 1, the larger the value of C_m, the lower the accuracy. To reduce approximation error, C_m should be as small as possible, but since the number of components N_c increases with decreasing C_m, which could slow down the computation and adversely affect the real-time performance. In this study, C_m is set to 0.5 and the maximum error is 0.044 mm which is negligible when compared with the fit criterion. The original plate model is then decomposed into 182 convex components. It has little effect on the frame rate under the hardware configuration of the proposed system, which will be discussed in the next section. As shown in Fig. 5, many small convex components are created around the regions where the geometry of the plate is more complex. The approximation error is visually depicted in Fig. 6 using surface-error map.

Table 1
Model decomposition error.

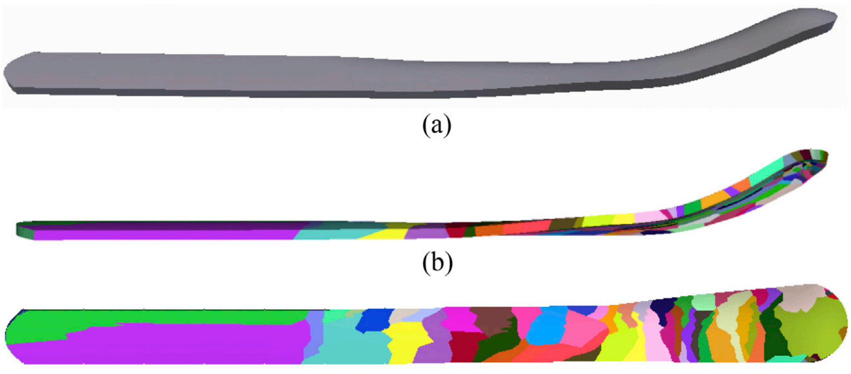
C_m	N_c	Error (mm)		
		Max	Mean	RMS
0.1	1052	0.007	0.000	0.000
0.5	182	0.044	0.003	0.008
1	93	0.100	0.008	0.018
2	51	0.191	0.022	0.041
3	35	0.303	0.038	0.071
4	29	0.410	0.051	0.09
5	24	0.499	0.075	0.132
6	23	0.586	0.087	0.153
7	18	0.718	0.109	0.176

3.4. Model decimation

The data of the bone models used in this study are acquired by CT scan, which produce high-resolution models containing hundred thousands of vertices and triangles (see Fig. 7). Directly using such models is computation-intensive and the refresh rate can drop to less than 10 frames per second (fps) in the proposed system. This is unacceptable for the real-time interactive applications. Model decimation by edge collapse is thus used to reduce the complexity of the bone model while keeping the resolution high enough for simulation. To achieve optimal trade-off, experiments are carried out to investigate the relationship between refresh rate and model resolution. It can be seen from Fig. 8 and Table 2 that when the vertex count is reduced to 4% of that of the original model, the refresh rate is 60 fps which is suitable for interactive applications, and the approximation error is less than 0.29 mm which can be neglected when compared to the fit criteria. This setting is thus adopted in the proposed system. The corresponding surface-error map is shown in Fig. 9.

3.5. Collision detection and response

Despite being rigid bodies, the bone and plate models contains thousands of triangles which makes simple collision detection methods, e.g. pair-wise testing, computationally inefficient for real-time performance [28]. A two-phase collision detection technique is adopted here to reduce the amount of computation required [29]. It includes a broad phase and a narrow phase. The former identifies disjoint groups of possible intersecting objects, whereas the later prunes the unnecessary primitive pair testing. The broad-phase collision detection is achieved via the Bounding Volume Hierarchy (BVH) which organizes the triangles of the bone model recursively with a tree structure as shown schematically in Fig. 10. Since the changes in position and orientation of the bone model require re-building of the BVH, in view of computation efficiency,


(a)

(b)

(c)

Fig. 5. The plate model is decomposed into 182 convex components ($C_m = 0.5$), which are indicated with different colours: (a) the original model, (b) the side view and (c) the top view of the decomposed models.

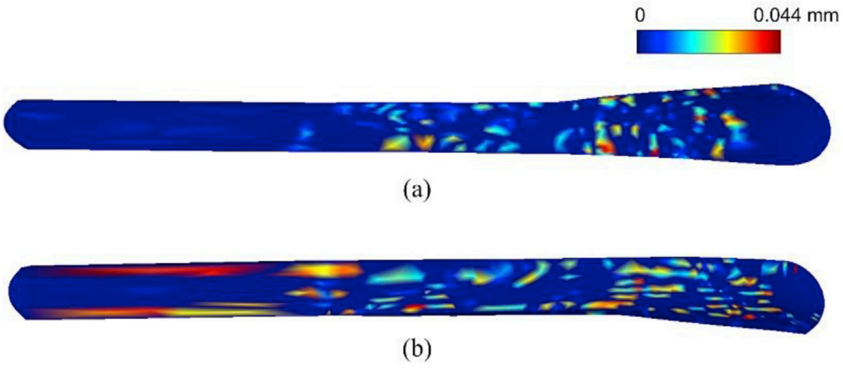


Fig. 6. The surface-error map of the decomposed plate model based on the Hausdorff distance: (a) top view and (b) bottom view. The surface difference between the original model and the approximated model are computed by projection onto the original one.

the bone model is fixed in the system whereas the plate can be moved for fit assessment. The convex components of the decomposed plate model, as explained in Section 3.3, is used for detecting collisions with the bone using the fast Gilbert-Johnson-Keerthi algorithm [30] and the expanding polytope algorithm [31].

Virtual coupling [21,32] is used to improve the stability of the haptic rendering system so that feedback forces can be updated at high frequency while the dynamics and graphics of the virtual environment are simulated at a slower rate. This will be discussed in Section 3.6. In the system, rigid body dynamics, under the influence of contacts and friction, is computed using iterative constraint solver [33], where internal reaction forces and torques are considered for each constraint. When collision is detected, the Baumgarte scheme is used to separate the colliding bodies [34]. The equations of motion, subject to various constraints, is solved by the projected Gauss-Seidel algorithm.

3.6. Haptic rendering

For simple haptic rendering concerning 3 dof, the interaction forces can be calculated by the penalty depth (or coupling distance) derived

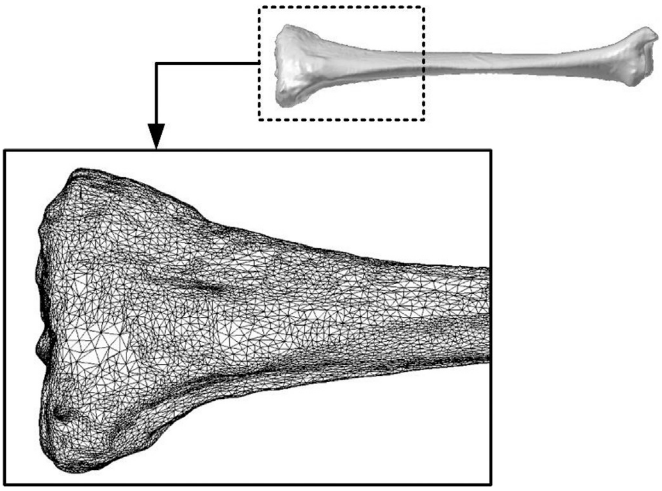


Fig. 7. CT-reconstructed proximal tibia model.

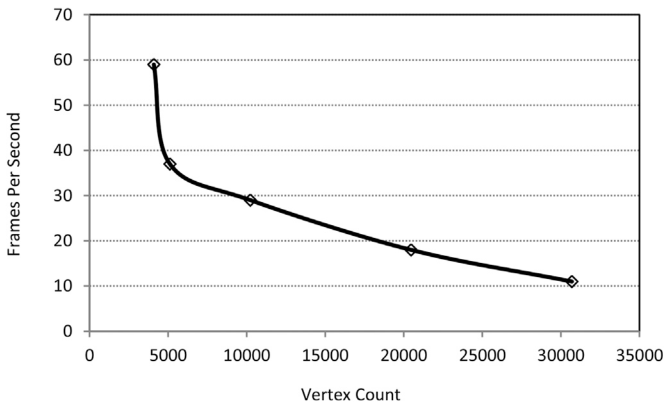


Fig. 8. The plot of refresh rate and vertex count of the bone model.

Table 2
Model decimation and the approximation errors.

Decimation Factor[a]	Number of Vertices	Number of Triangles	Hausdorff Distance (mm)		
			Max.	Mean	RMS
1.00	102323	204642	0.000	0.000	0.000
0.30	30698	61392	0.137	0.006	0.010
0.10	10234	20464	0.162	0.016	0.023
0.08	8187	16370	0.200	0.019	0.026
0.06	6141	12278	0.412	0.024	0.032
0.04	**4094**	**8184**	**0.286**	**0.032**	**0.043**
0.02	2048	4092	0.391	0.055	0.071
0.01	1025	2046	0.681	0.092	0.120

The significance of bold shows that when the decimation factor is 0.04, the number of vertices can be reduced to a level such that the refresh rate can be maintained at 60 fps. As indicated from Fig. 8, the required number of vertices is about 4000.

[a] e.g. a factor of 0.1 refers to the reduction of the number of vertices and triangles to 10%.

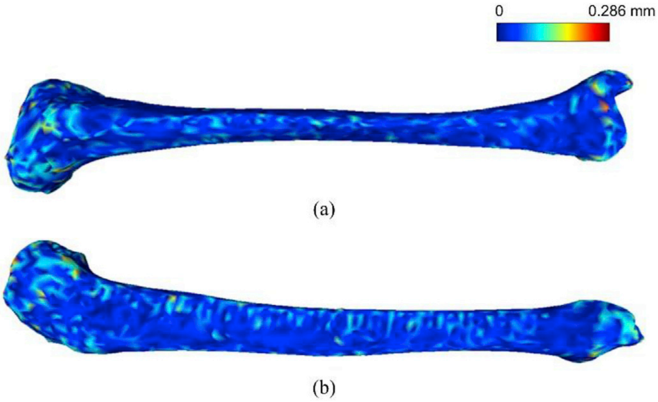


Fig. 9. The surface-error map of the decimated bone model: (a) side view, (b) top view.

from the distance between the haptic cursor and virtual objects [21], using the god-object [9] or finger-proxy [10] algorithms. For 6-dof haptic rendering, more robust algorithms are needed to overcome instability caused by the addition of artificial energy into the simulation system [35, 36]. In the proposed system, the virtual coupling algorithm is applied [21]. Refer to Fig. 11, a damped spring is introduced between the plate and the device proxy, and the device proxy is controlled directly by the haptic interface. In Loop #1 which runs at 1 kHz (haptic refresh rate), the position and orientation of the proxy are updated and the forces are calculated, whereas in Loop #2 which runs at 60 Hz (simulation/-graphics refresh rate), the states of the plate are calculated and updated. The virtual coupling control $\tau_k \in \Re^n$ for the haptic device at time step k is defined as [37],

$$\tau_k := -b \cdot \dot{y}_k - B \cdot (\dot{y}_k - \dot{x}_k) - K \cdot (y_k - x_k), \qquad (3)$$

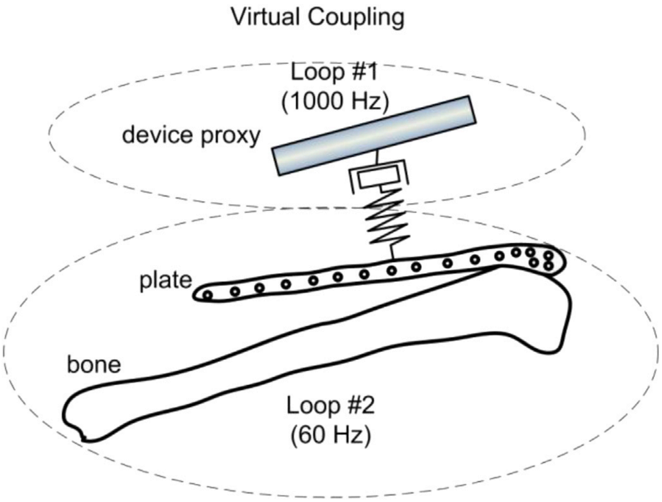


Fig. 11. Schematic representation of virtual coupling for the plate placement system.

where $y_k \in \Re^n$ is the device configuration sampled at τ_k, n is the dof of the haptic device, $\dot{y}_k$is the velocity of the device, b is the minimum device damping, $B, K \in \Re^{n \times n}$ are virtual coupling gains, x_k is the configuration of the plate, $\dot{x}_k$ is the velocity of the plate at sampling time τ_k. Then, the control forces are scaled by a negative factor and applied to the plate for dynamic simulations. The spring-damper model of the virtual coupling algorithm can be used not only for updating the plate's position and orientation and calculating the forces, but also computing the torques during the interactions. However, the latter is not considered here since the haptic device employed does not produce torque feedback.

4. Implementation

The proposed system is implemented on a personal computer with an Intel Core i7-2600 3.4G Hz processor, 4 GB RAM and an NVIDIA Quadro 4000 graphics display card, running Microsoft Windows 7. The computer is connected to the Geomagic Touch haptic device for providing 6-dof positional inputs and 3-dof force outputs. Software development kits (SDK) are used for the programming of the system. The physics simulation engine Bullet SDK is utilized to implement the collision detection algorithms and dynamics simulations, the OpenHaptics SDK for haptics simulation, the OpenGL SDK for graphics simulation, and the AntTweakBar library for simulating the lighting in the virtual environment and building the graphical user interface.

In the system, interactive visual cues are provided to facilitate the placement process. Based on the fit criteria, the distance between the plate and the bone is visualized by attaching thin and short line segments

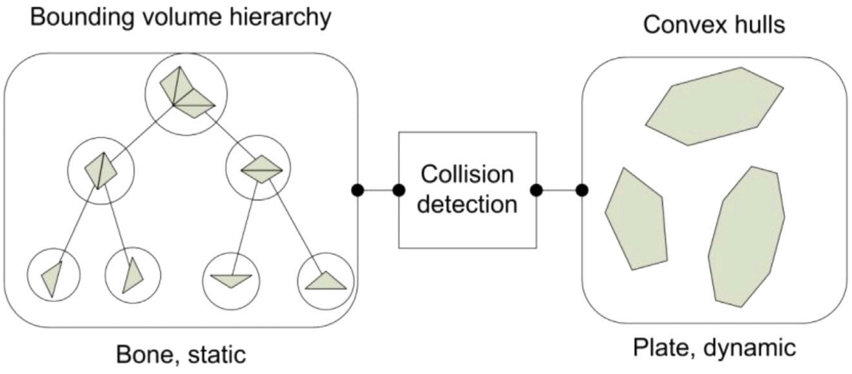


Fig. 10. Collision detection using BVH and convex hulls.

on the plate, as shown in Fig. 12. These lines are perpendicular to the plate, projecting from the points where plate-bone distances in the fit criteria are calculated. The lines are coloured in red when the fit criteria are not met; they are drawn in green otherwise. Besides, wireframe boxes are used to indicate the parts of the plate that are colliding with the bone, also shown in Fig. 12. When plate-bone collisions occur, wireframe boxes are displayed and attached locally on the plate, around the location where collision occurs.

Fig. 13 and Fig. 14 show the data recorded by the system in a plate placement trial, including the task completion time, position and velocity of the plate, feedback forces and fitting errors. It can be seen from Fig. 13 that the force is small when the plate is relatively far away from the bone but increases more significantly when it is getting close to the optimal placement location. It means that at the beginning the user manipulates the plate with large displacement without colliding the bone, where plate placement at this stage is mainly based on visual feedback. When the plate is approaching the optimal location, e.g. around the point Q as indicted in Fig. 13, plate-bone collisions occur and feedback forces are generated whereby the user can fine tune the plate's position and orientation in addition to the visual feedbacks. The mean plate-bone separation and the angular error during the placement process are shown in Fig. 14. They both decreases gradually as the plate approaches the bone, and fluctuations when the user is searching for the optimal location by trial and error with the aid of visual and haptic feedback in the virtual environment.

5. Evaluation

To evaluate the effectiveness of the proposed method, an experiment was conducted to compare the completion time of using virtual trackball and 3D haptic user interface device respectively to place the fixation plate. Twenty-two subjects were recruited to participate in the study. They were undergraduate students from various disciplines (e.g. computing, nursing, physiotherapy and radiography) and the average age was 22.91 years. Before the experiment, introduction of the proposed system and demonstration on the operations were given to the subjects. They were also allowed to practise briefly using virtual trackball and 3D haptic device before the experiment. Each of them was then asked to perform virtual plate placement twice, once with virtual trackball and the other with 3D haptic device. The order of using the two methods was randomized to average out learning effect, if any, such that half of the subjects used virtual trackball first, while the other half used 3D haptic device first. After the experiment, the subjects were also asked to rate their satisfaction on the user interface of the two systems by responding to the question “How well do you like using the interface of the system?” on a 7-point Likert scale, with 1 indicating least satisfied and 7 most satisfied. The results of the experiment are shown in Table 3. The mean completion time of using virtual trackball with 2D mouse and 3D haptic device to perform plate placement was 99.45 and 21.73 s respectively. Paired *t*-test shows that the difference is statistically significant, indicating that the proposed method of using 3D haptic device to locate the optimal plate location is a more efficient approach. On the other hand, the mean satisfaction rating of the 3D haptic device was found to be 1.59 points higher than that of the virtual trackball, which is of statistical significance as indicated by a p value of less than 0.05 from two-tailed Mann-Whitney *U* test.

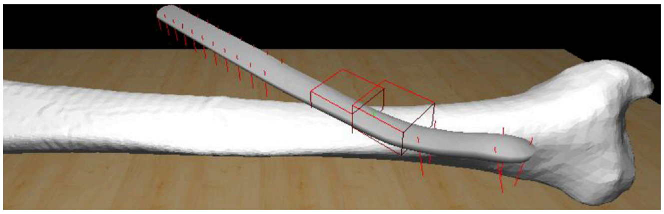


Fig. 12. Visual cues assisting virtual plate placement.

6. Discussions

In the paper, a virtual fixation plate placement system is proposed for the determination of the optimal position of the pre-contoured fixation plate on the distal medial tibia. The system is equipped with 3D haptic device and provides interactive feedback forces to assist in fixation plate placement. Experimental results suggest that this approach is more effective for performing plate placement than the conventional approaches that employ virtual trackball. Feedback from the subjects also suggests that 3D haptic interface is a more natural and favourable hardware user interface for manipulating the virtual plate to determine the optimal placement.

In the development of the system, fast and accurate collision detection is necessary for prompt generation of interactive feedback forces, whereas accurate geometric modelling of bone is required for the determination of optimal plate position. However, the two requirements are conflicting and is tackled in the study by reducing the complexity of the CT-reconstructed bone model by decimation, so that the collision detection algorithm can execute at interactive rates, while the error of the reduced model remains reasonably small relative to the fit criteria. To further enhance the robustness of collision detection, the predictor-corrector approach has been implemented where the next position of the plate is first predicted at each time step by approximated numerical integration, and then corrected based on the conservation of momentum and other physical constraints [38].

On the other hand, the geometrical model of the fixation plate is modified using convex decomposition to facilitate collision detection and dynamic simulation. The modified version of the plate model can approximate the original one more accurately when more convex components are created from the concave counterparts. However, the computational efficiency can be decreased significantly by the increasing number of convex components created. Since the optimal trade-off condition cannot be adjusted directly in the HADC algorithm adopted in the study, it is achieved experimentally in a trial-and-error manner such that the concavity of the model and the approximation error are reasonably small while the number of convex components created is only moderate.

The idea proposed in the paper is realised using distal medial tibia as an illustration. It can be extended for pre-operative planning in orthopaedic surgery concerning fractured bones in other anatomical sites, where the fit criteria for optimal placement of the fixation plate will be changed accordingly. Also, the extent of decimation of the CT-reconstructed bone model and the degree of convex decomposition of the fixation plate model will need to be evaluated to facilitate real-time collision detection and dynamic simulation. Further research will be conducted to investigate the system usability and the role of haptic feedback in the placement process.

7. Conclusions

The study shows that virtual fixation plate placement can be conducted more intuitively and effectively with the aid of 3D user interface and interactive feedback forces. Visual cues showing on the fly the extent of agreement with the fit criteria are also helpful guidance for locating the optimal location of plate placement. The proposed system will be further evaluated by studying user performance under different conditions, e.g. employing 3D user interface device with or without force feedback, or at different difficulty levels by tightening or relaxing the margin of the fit criteria. System usability and user satisfaction will also be investigated. Moreover, research will be conducted to further demonstrate the feasibility of the proposed fixation plate placement system by including virtual models of different types of pre-contoured fixation plates and fractured bones at different anatomical sites.

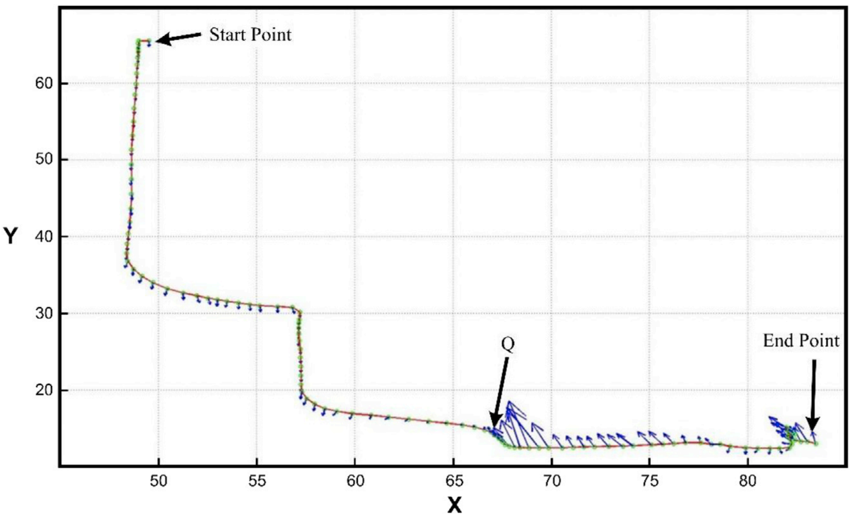
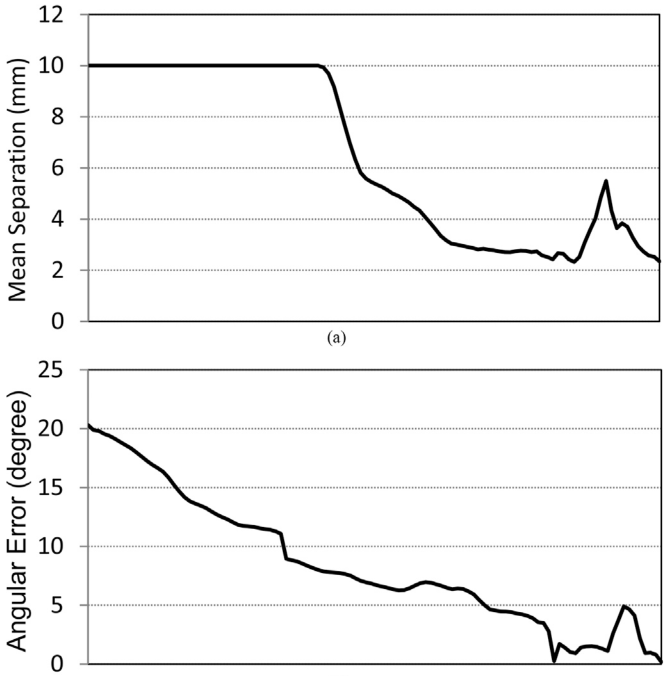


Fig. 13. Variations of plate position in the X-Y plane in a placement trial. The blue arrows drawn on the path denote the interaction forces during the process.



(a)

(b)

Fig. 14. (a) Mean plate-bone separation and (b) angular error over time during the placement. In (a), the mean separation is capped at 10 mm which means the plate is too far away from the bone.

Table 3
Completion time and satisfaction rating.

User Interface	Completion Time (seconds)			Rating of Satisfaction (1 = worst, 7 = best)		
	Mean	SD	p-value	Mean	SD	p-value
Virtual trackball	99.45	40.36	1.06×10^{-7}	4.23	1.82	5.78×10^{-3}
3D haptic device (proposed method)	21.73	17.39		5.82	0.85	

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