Journal of Biomedical Informatics 48 (2014) 122–129

Contents lists available at ScienceDirect

Journal of Biomedical Informatics

journal homepage: www.elsevier.com/locate/yjbin

Development and validation of a surgical training simulator with haptic feedback for learning bone-sawing skill

Lin Yanping [a], Wang Xudong [b,*], Wu Fule [a], Chen Xiaojun [a], Wang Chengtao [a], Shen Guofang [b]

[a] School of Mechanical Engineering, State Key Laboratory of Mechanical System and Vibration, Institute of Biomedical Manufacturing and Life Quality Engineering, Shanghai 200240, China

[b] Shanghai Ninth People's Hospital Affiliated to Shanghai Jiao Tong University, School of Medicine, Shanghai 200011, China

ARTICLE INFO

Article history:
Received 1 July 2013
Accepted 13 December 2013
Available online 28 December 2013

Keywords:
Surgical training simulator
Bone sawing
Haptic
Skill learning
Simulator validation

ABSTRACT

Objective: Bone sawing or cutting is widely used for bone removal processes in bone surgery. It is an essential skill that surgeons should execute with a high level of experience and sensitive force perception. Surgical training simulators, with virtual and haptic feedback functions, can offer a safe, repeatable and cost-effective alternative to traditional surgeries. In this research, we developed a surgical training simulator with virtual and haptic force feedback for maxillofacial surgery, and we validated the effects on the learning of bone-sawing skills through empirical evaluation.
Methods: Omega.6 from Force Dimension was employed as the haptic device, and Display300 from SenseGraphices was used as the 3D stereo display. The voxel-based model was constructed using computed tomography (CT) images, and the virtual tools were built through reverse engineering. The multi-point collision detection method was applied for haptic rendering to test the 3D relationship between the virtual tool and the bone voxels. Bone-sawing procedures in maxillofacial surgery were simulated with a virtual environment and real-time haptic feedback. A total of 25 participants (16 novices and 9 experienced surgeons) were included in 2 groups to perform the bone-sawing simulation for assessing the construct validity. Each of the participants completed the same bone-sawing procedure at the predefined maxillary region six times. For each trial, the sawing operative time, the maximal acceleration, and the percentage of the haptic force exceeding the threshold were recorded and analysed to evaluate the validity. After six trials, all of the participants scored the simulator in terms of safe force learning, stable hand control and overall performance to confirm the face validity. Moreover, 10 novices in 2 groups indentified the transfer validity on rapid prototype skull models by comparing the operative time and the maximal acceleration.
Results: The analysed results of construct validity showed that the two groups significantly reduced their sawing operative times after six trials. Regarding maximal acceleration, the curve significantly descended and reached a plateau after the fifth repetition (novices) or third repetition (surgeons). Regarding safe haptic force, the novices obviously reduced the percentage of the haptic force exceeding the threshold, with statistical significance after four trials, but the surgeons did not show a significant difference. Moreover, the subjectively scored results demonstrated that the proposed simulator was more helpful for the novices than for the experienced surgeons, with scores of 8.31 and 7.22, respectively, for their overall performance. The experimental results on skill transference showed that the experimental group performed bone-sawing operation in lower maximal acceleration than control group with a significant difference ($p < 0.05$). These findings suggested that the simulator training had positive effects on real sawing.
Conclusions: The evaluation results proved the construct validity, face validity and the transfer validity of the simulator. These results indicated that this simulator was able to produce the effect of learning bone-sawing skill, and it could provide a training alternative for novices.

1. Introduction

Bone sawing or cutting is a complex hard tissue removal process applied in bone surgery (orthopaedic surgery or cranio-maxillofacial surgery) that involves many steps in which different essential skills are required. The surgeon must be very careful to apply appropriate forces and to operate the tools at appropriate speeds to avoid over-operation. Becoming a skilful surgeon with sensitive force perception requires rigorous training and iterative practice. Traditionally, surgical trainees have often watched and performed operations on models, animals or cadavers under the

* Corresponding author.
E-mail address: xudongwang70@hotmail.com (X. Wang).

1532-0464/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.jbi.2013.12.010

supervision of experienced surgeons, before performing the procedures themselves. This surgical education system has many drawbacks in terms of efficiency, cost, flexibility, and safety [1,2].

Visuo-haptic interactive simulators, with both visual and haptic (tactile) feedback, have been rapidly developed in recent years to provide a realistic, cost-effective, safe and repeatable alternative to traditional surgical training methods, and these simulators have played an increasing role in surgical education and training [1,3]. Virtual reality systems have used computers to create virtual environments for simulating real-world scenarios, and haptic devices have been employed to assist in surgical training through virtual simulations of surgical procedures with haptic feedback. These visuo-haptic simulators can provide tactile, visual and audio sensations or information to create a realistic training scenario, in which novice surgeons can practice surgical operations, thus allowing them to make mistakes without serious consequences. As a result, the pre-trained novice can practice to master the basic skills and can undertake cognitive planning of surgical tasks [4].

The aim of this research was to simulate bone-sawing operations and evaluate the validity of the learning of bone-sawing skill among trainees. For bone surgeries, bone-machining tasks are force skills, which require the trainee to operate the tools at an appropriate feed velocity with a stable hand and to remember the quantity of force applied to the tool. It is a challenging task to create realistic haptic interactions between a high spindle-speed saw, operating at more than 10,000 rpm (revolutions per minute), and stiff bone. In this study, we constructed a virtual bone model for haptic rendering, based on the voxel model [5], and it had the advantage of taking into consideration the heterogeneous properties of materials. Further, the major variables (bone density, feed velocity and spindle speed) were considered in calculating the haptic forces of the bone-sawing operation. Moreover, we employed the multi-point collision detection method [6] to test the interaction between the tool and the virtual bone model, with the hope of achieving more real haptic forces. To evaluate the construct validity, face validity and transfer validity of the proposed simulator, three experiments were included in this study to analyse the effects of the learning bone-sawing skill.

The rest of the paper is organized as follows: Section 2 introduces the related previous work. Section 3 presents the development of the simulator with graphic rendering and haptic rendering. The simulator validity is tested in Section 4 with a multi-tiered testing strategy. Section 5 is the discussion and conclusion.

2. Related work

Recently, many researchers have undertaken studies to improve the bone-machining interactions in arthroscopy [7], dental surgery [8,9], orthopaedic surgery [10,11] and cranio-maxillofacial surgery [12,13]. Most of the research into bone-machining simulations has focused on bone-drilling [10,14], burring [12,15,16] or milling [17] processes because the drill head can be easily approximated with a simple shape (sphere or cylinder), and the collision detection is less time-consuming [13]. As bone sawing or cutting is the one of the most important basic skills that is applied in bone surgeries, it was necessary to develop a visuo-haptic training simulator for bone-sawing procedures. Hsieh et al. [18] developed an amputation simulator with bone-sawing haptic interaction to simulate the distal femur being separated with an oscillating saw, but many major coefficients (cutting velocity and feed rate) were neglected in the haptic force computation. Wang et al. [19] developed a surgical simulator for mandibular angle reduction with a reciprocating saw and a round burr, based on an impulse-based rendering method with a surface mesh model. Chen et al. [20] presented a haptic and visual surgery training platform prototype to perform cutting of the cranium using a force feedback function, in which the cutting function module with only a single-point sensor.

In our paper, a visuo-haptic training simulator is proposed for bone-sawing based on voxel model and multi-point collision detection method. Bone density, feed velocity and spindle speed of the saw were considered to compute the haptic forces. Multi-threading computation environment was implemented to asynchronously rendering the graphic and haptic simulation.

For effective learning of surgical skills using surgical training simulators, many researchers have reported several methods to evaluate different types of validities [21]. There have been a number of studies of skill assessments for simulators of laparoscopy [22] and endoscopy [23], and many researchers have contributed efforts in bone-drilling or burring skill evaluations [11,24,25]. Morris et al. [24] showed that, for bone-machining simulations, learning with visuo-haptic feedback was significantly better than learning the same tasks with visual feedback alone [26]. However, to the best of our knowledge, the research into the training effects of the learning of bone-sawing skill has been very scarce [19]. Wang et al. [19] evaluated an impulse-based simulator regarding its ability to train. Fourteen volunteers, in two groups, were included in their study to confirm the face validity and construct validity of the simulator. However, the skill transference and skill retention were not discussed in their study.

In our paper, three experiments are conducted to evaluate the construct validity, face validity and transfer validity of the proposed simulator in learning bone-sawing skill.

3. Simulator development

In this study, Omega.6 from Force Dimension was employed as the haptic device. The Omega.6 is a pen-like haptic device, and it has 6 degrees of freedom (6DoF) and 3 degrees of force feedback (3DoFF). True 3D stereo performance in high resolution was shown on the Display 300 from SenseGraphices, which employs shutter glasses technology together with a high-performance 120 Hz LCD monitor. The following sections detail the design and development of the bone-sawing simulator.

3.1. Graphic rendering

For virtual surgery, high visualisation quality and real-time display are essential for a realistic simulation. This simulator utilised the well-known marching cube algorithm [27] to obtain polygon mesh from CT scans of 0.625 mm in slice thickness. The cranio-maxillofacial model, with important anatomical objects, including skin, teeth, gingiva, tongue and the inner oral wall, was refined, and the photo textures were added for visual interaction (Fig. 1). The bone removal process was represented by the voxel-based model [5], which enabled the implementation of volume structural changes and which considered the heterogeneous properties of the bone. During the bone-sawing simulation, once the virtual tool collided with the voxel-based model, the virtual model continuously changed and updated to simulate bone deformation. With the voxel-based haptic simulator, the interactive manipulation of huge datasets in real time was a challenging issue. The more complex the model, with voxels of small size, was constructed, the more computational time was needed for the simulation. To achieve a balance between computing complexity and realism in real time, we constructed the voxel-based model at a size of $0.3 \times 0.3 \times 0.3$ mm [28] in the vicinity of the operative region to simulate bone-sawing processes.

Virtual tool modelling was the other important part of the virtual environment because the geometry or representation of the tool was essential to collision detection, force computation, haptic