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Design and implementation of a maxillofacial surgery rehearsal environment with haptic interaction for bone fragment and plate alignment

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Purpose
The treatment of patients with complex facial and neck trauma is one of the most challenging multidisciplinary tasks in surgery. Simulation technology based on 3D data of an individual patient will have a critical impact on surgical planning and training. Repair of maxillofacial fractures involves aligning fragments of bone with accuracy so that aesthetics and function are restored. Surgery is often lengthy and hindered by inability to fully view the fractures from all angles due to anatomic difficulties such as muscular attachments, vascular supply and critical nerve supply.

On-site and remotely accessible virtual environments capable of simulating interactions with patient-specific anatomy will allow surgeons to plan and rehearse operations and to retrain skills for infrequent procedures. Selection of type of plate, its length, alignment and screw length is currently done intraoperatively and several alternatives might need to be considered in the operating room. The ability to shift these decisions to a pre-operative planning stage would decrease the length of surgery and improve confidence in the accuracy of repair.

Research and commercially available maxillofacial surgery planning software allows for interactive realignment of fractures based on segmented, pre-operative CT images, but are limited to the interactions of keyboard and mouse [1], or a 2D pen tool [2]. This limited ability to control orientation of the bone fragments and lack of force feedback on contact leads to low perceived confidence of the resulting surgical plan. Optically tracked plaster models have been suggested to link conventional planning techniques with computer assisted visualization [3].

Our goal is to overcome the limitations of current software by designing and implementing a haptics-enabled maxillofacial surgery rehearsal environment that requires little training and provides a direct high-fidelity immersive experience for the operator, without use of plaster models. The system would support six degree-of-freedom (6-DOF) haptic interaction for bone fragments and plate alignment for pre-surgical planning to treat mandibular fractures. Our aim is to evolve a design of real utility to surgeons and, at the same time, ensure that it can be realized in implementation by identifying and addressing the technological and interaction design challenges through conceptual and technical prototypes.

Methods
The design process has followed a user centered design method concurrently with development of state-of-the-art collision detection and haptic rendering algorithms. This dual process allows for identification of requirements that may be met with currently available technology as well as opportunities for improvements in certain essential technological areas of particular value to this project. The design is informed and iteratively improved by field studies, lo-fi and hi-fi prototypes, scenarios and co-operative evaluation with oral/maxillofacial surgeons.

During the design process we are iteratively implementing two main prototypes, following the concepts of a vertical (few features, but hi-fi interaction) and a horizontal (conceptually all features of the system, but lo-fi interaction) prototype. The horizontal prototype allows the surgeon to execute a typical usage scenario from beginning to end. While not all features are fully implemented, and some may only be mock-ups, the purpose of the horizontal prototype is to elicit feedback and modify the prototype and scenario to identify the most important aspects of the system. The risk with a horizontal-only prototype is that the designer might use materials and technologies that are infeasible or even impossible to implement. We balance this risk with vertical prototypes that fully implement critical components requiring new technologies, which act as proof of concept and informs the overall design of what can be built.

One essential property of the rehearsal environment is the possibility of bi-manual six degree of freedom positioning and orientation of fractured mandibular bone in a way that looks and feels reassuring, without requiring the user to learn a complex CAD-like system. Real-time visualization of the dental occlusion and haptic feedback conveying accurate contact forces while manipulating fractured bone fragments are essential components of the system, and thus novel technological development in these areas is required.

Results
The steps and interactions we identified include loading a segmented CT-scan of a trauma patient, viewing it in a stereoscopic display co-located with a bi-manual haptic interface, manipulating the bone fragments, and perceptualizing the occlusion between maxilla and mandible both visually and haptically through force-feedback. In addition, the surgeon may lock the fragments into key positions, view them from different directions, decide on plate placement and screw sizes, and finally generate a report of the resulting surgical plan. The form of our initial prototype was a pure mock-up (figure 1), and was used as a conversation artifact to improve the design and build common ground between surgeons and engineers.

Our studies indicate that the success of such a system is highly dependent on the fidelity of the haptic rendering. For the rehearsal environment to be intuitive, the interaction must follow the direct intention of the operator with smooth and accurate force feedback. A vertical prototype (figure 2) has been developed to focus on the haptic rendering aspect of the system. It extends our group's previous work [4] to formulate a new algorithm for rendering 6-DOF haptic interaction between high-resolution volumetric representations of objects (e.g. bone fragments from CT images). In addition to the prototypes, we will report the results of an formative evaluative study, which will include the grading of perceived usefulness and fidelity of the interaction.

Conclusion
We show a maxillofacial surgery rehearsal environment that was developed using an iterative design process with feedback from surgical specialists. The system will permit surgeons to plan, simulate and rehearse complex repair of maxillofacial fractures, including bone fragment and bone plate alignment in three-dimensional space. The benefit of a haptics-enabled system for obtaining accurate surgical results, reducing operating time, and for enabling a platform to enhance surgical training in infrequent operations is considered.

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[Image 1 here]
Figure 1. The first prototype consists of only mock-up components. It provides a likely set-up where the surgeon can feel collision forces between fractured segments of the mandible and occlusion with the maxilla, in a stereoscopic virtual environment (viewed through a mirrored display, here represented by a transparent window) that provides visual perspective shifting with head movement.

[Image 2 here]
Figure 2. Screenshot from the interactive prototype. Each of the two mandibular fracture segments can be moved with a left and a right haptic device respectively.

fig.1

fig.2


H3D