On Virtual Surgical Planning in Cranio-Maxillofacial Surgery

JOHANNA NILSSON
Abstract

The complex three-dimensional (3D) anatomy of the cranio-maxillofacial (CMF) region makes surgery a challenging task. Virtual surgical planning (VSP) has the potential to increase accuracy, reproducibility and shorten operation time. Key challenges in VSP are to accurately separate, or segment, certain structures of interest, such as the orbit, from the rest of the image, as well as to create an accurate 3D model of the facial bones and dentition for orthognathic surgery planning. The time required for planning and fabrication of guides for trauma surgery is another challenge. The overall aim of this thesis was to develop and evaluate new virtual planning tools for CMF-surgery and to investigate their usefulness. Study I, II discuss and evaluate image fusion of CT/CBCT and intraoral scanning for orthognathic surgery. A method for virtual bite registration in centric relation (CR) was also proposed. The workflow has the potential to eliminate traditional laboratory work, and may facilitate 3D computer-assisted-planning in orthognathic surgery. Study III deals with orbit segmentation and presents a semi-automatic method, using a deformable model tracing the inside of the orbit via haptic 3D interaction. The method was validated in retrospective unilateral orbital fracture cases. The fractured orbits were compared to the intact side by volume and shape analyses. The method showed high accuracy, precision, time-efficiency and thereby potential to be a powerful tool for planning and evaluating reconstruction of orbital fractures. Study IV evaluates an in-house haptic-assisted VSP system for complex mandibular fractures on a series of retrospective cases and an artificial case. The system showed high precision and time-efficiency, but relatively low accuracy. This study proposes a novel, fast and user-friendly way of integrating VSP into planning mandible trauma surgery and could help in reducing operating time and increase accuracy. Study V is a systematic review and meta-analysis studying potential time benefits using VSP in CMF surgery. The study suggests that VSP shortens the operating time and ischemia time for reconstructive surgery. VSP also appears to shorten the preoperative planning time for orthognathic surgery.

Keywords: Virtual surgical planning. Computer assisted planning. 3D computer model. Orbital segmentation. Cranio-maxillofacial surgery planning. Haptics.

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To Sven & Viggo
List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


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Related Work

In addition to the papers included in this thesis, the author has also written or contributed to the following publications.


II  Nysjö J, Nilsson J, Malmberg F, Thor A, Nyström I. Rapid and precise orbit segmentation through interactive 3D painting. (manuscript)
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**Abbreviations**

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<th>Full Form</th>
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<tbody>
<tr>
<td>3D</td>
<td>Three-Dimensional</td>
</tr>
<tr>
<td>CBCT</td>
<td>Cone beam Computed Tomography</td>
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<tr>
<td>CMF</td>
<td>Cranio- Maxillofacial</td>
</tr>
<tr>
<td>CR</td>
<td>Centric Relation</td>
</tr>
<tr>
<td>CT</td>
<td>Computed Tomography</td>
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<tr>
<td>HASP</td>
<td>Haptic Assisted Surgical Planning</td>
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<tr>
<td>HU</td>
<td>Hounsfield Unit</td>
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<tr>
<td>ICP</td>
<td>Iterative Closest Point</td>
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<td>IOS</td>
<td>Intraoral Scanning</td>
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<tr>
<td>MAD</td>
<td>Mean Absolute Distance</td>
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<td>MMF</td>
<td>Maxillomandibular Fixation</td>
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<tr>
<td>ORIF</td>
<td>Open Reduction and Internal Fixation</td>
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<tr>
<td>PSI</td>
<td>Patient Specific Implant</td>
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<tr>
<td>PVE</td>
<td>Partial Volume Effect</td>
</tr>
<tr>
<td>RP</td>
<td>Rapid Prototyping</td>
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<td>VSP</td>
<td>Virtual Surgical Planning</td>
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</table>
1. Introduction

1.1 Scope of the thesis

This thesis concerns the development and evaluation of virtual surgical planning (VSP) for cranio-maxillofacial (CMF) surgery and some of the challenges involved with this new technology. The included papers are the result of a close collaboration between clinicians and computer scientists, which has an important role in continuing the development of digital tools to improve surgical outcomes.

VSP is a pre-operative planning method that involves the visualization of a surgical procedure in a 3D imaging computer software. There are several benefits of VSP, including improved diagnostic accuracy and the possibility to simulate the surgery in the virtual environment.\textsuperscript{1-3} The computer-assisted surgery (CAS) can intra-operatively facilitate the surgery with cutting/drilling guides, patient specific implants (PSI), intraoperative navigation and intraoperative CT.\textsuperscript{4-6} Post-operatively, the procedure can be evaluated by image fusion or superimposing of two data sets.\textsuperscript{7} This allows the surgeon to accurately analyse the outcome with the preoperative state or the virtual plan. It is also possible to perform mirroring of the intact side to evaluate symmetry or volume differences.

The most important step in CAS is the development of an accurate 3D model of the anatomical structure of interest. This can be done through different kinds of medical imaging technologies including CT, CBCT, MRI, intraoral scanners, ultrasound etc. It is often necessary to combine different imaging methods by data fusion.\textsuperscript{8, 9} This is particularly relevant when planning surgery for orthognathic cases, where it is crucial to have a model that can present both the dentition and the facial bones with optimal accuracy. Another important step in VSP is the image segmentation. This is the process of separating objects/regions of interest from the rest of the image. This can be done by assigning a label to every voxel, in a 3D image so that voxels with the same label share the same certain characteristics, i.e. bone, vessels and soft tissue. A key challenge in CMF surgery is the segmentation of the orbit.\textsuperscript{10} This is due to both the anatomical location of the orbit and its thin walls, leading to individual voxels sharing information from both hard and soft tissue.
Several benefits with VSP and CAS are presented in the literature, but one disadvantage of the current planning setup is the time required for the preoperative planning, fabrication, and shipping of the guides or PSI.\textsuperscript{11} This has created opportunity for the establishment of an in-house VSP system, so the surgeon can perform all the steps of the planning and the fabrication of guides by him/herself. This could potentially lead to a broader indication area for VSP and also facilitate in trauma surgery, where inherent time pressures normally mean that VSP is not a viable option.\textsuperscript{12} This thesis is based on five studies, two discussing and evaluating the image fusion of CT/CBCT and intraoral scanning for orthognathic surgery, a third that deals with orbit segmentation, a forth that evaluates an in-house VSP system for complex mandibular fracture, and finally, a fifth paper that is a systematic review studying potential time benefits using VSP.

1.2 History and clinical applications for computer-assisted surgery

In recent years, 3D computer-assisted planning has spread widely for clinical applications in the field of CMF surgery.\textsuperscript{9, 13, 14} It has the potential to make postoperative outcomes more accurate, reduce operation time and improve the communication between the patient and the clinical team.\textsuperscript{1, 15}

The first approaches to 3D modelling, computer-aided design (CAD) and computer-aided manufacturing (CAM), were introduced in the car and aerospace industry during the 1970s and showed benefits of increased productivity and predictable outcome in the manufacturing. During the same era, Godfrey Hounsfield developed and introduced computed tomography (CT) imaging for medical purpose. For the first time, it was now possible to perform a scan on a living human in 3D.\textsuperscript{16} This opened up the possibility of translating the CAD/CAM technique from the industry into the field of medicine and dentistry.\textsuperscript{17, 18}

The application of 3D modelling in the field of CMF surgery started in the 1980s, using an anatomical model built from CT scan slices.\textsuperscript{19} It was not until the introduction of rapid prototyping (RP) and the use of selective laser sintering (SLS) and stereolithography (SLA) that made it possible to print accurate models for planning CMF procedures. In comparison to previous techniques, RP technology uses the principle of building up the model in layers rather than cutting it out from a single block.\textsuperscript{20} Using this new technology, surgeons were able to get a full-size model to plan the optimal bone graft donor site or use the model as a guide for implant manufacturing.
VSP in the field of CMF has developed rapidly during the past several decades. It is already well established in orthognathic surgery, reconstructive surgery, and several studies have showed increased efficiency and accuracy.\textsuperscript{1-3, 15, 21} In orthognathic surgery planning, virtual osteotomies can be performed, simulating the new positions of the jaws. In the simulation, mathematical calculations help predict how the surrounding soft tissue will respond to skeletal movements.\textsuperscript{22} Changes in the airway space and other soft tissue structures can also be analysed and preoperatively predicted with the aid of 3D simulations. Currently, there is an extensive research interest in patients with sleep apnea caused by narrow pharyngeal airway space, and the ability of virtual surgical planning to study and predict the increase of volume after orthognathic surgery.\textsuperscript{23}

Orbital deformities caused by congenital malformations, or as a result of trauma or tumours, are a great challenge for the CMF surgeon. VSP has the potential to simplify the preoperative assessment and postoperative evaluation by providing shape and volume analysis. VSP can also be used to create patient-specific implants for the orbit. However, it may be difficult to translate the preoperative plan into an actual outcome, which has led to an increased interest in the possibility for navigation techniques during surgery. Navigation relies on special instruments that are tracked by a navigation system and shows the relation to the patient’s anatomy in real time. This can be particularly useful in situations where the surgeon cannot see and evaluate the position of the instrument, e.g. the posterior positioning of a reconstruction implant in the orbit.

Planning and installation of dental and craniofacial implants is another area significantly affected by the influence of 3D visualisation and simulation. With the help of virtual planning, drill guides or templates can be individually manufactured to assure that the implants are positioned in areas with the best bone quality in a safe and predictable way.\textsuperscript{24}

In the field of CMF reconstruction, different types of free flaps, including the fibula, iliac and scapula, are used in the treatment of extensive defects caused by tumours or other lesions.\textsuperscript{25, 26} Fibular free flap is the most common vascularised bone transplant for mandible reconstruction. The fibula has a suitable dimension, bone quality and pedicle length. Shaping the graft to the bony defect is a challenging task that is highly critical for the functional and aesthetic outcome. The procedure should also be performed relatively fast in order not to jeopardize the flap survival. The ischemia time and operative time are known prognostic factors for free-flap survival and other postoperative complications.\textsuperscript{27} VSP and preoperative fabrication of guides and implants are already well established in reconstructive surgery and have showed reduced time required in the shaping of the transplanted bone, re-
duced ischemia time and improved fit of the bone in the reconstructed area.\textsuperscript{1, 28, 29}

The recent explosion of scientific and technological knowledge has led to a revolution in imaging techniques and virtual planning across a range of disciplines.\textsuperscript{13} CAS is likely still only in the beginning of a transformation in surgery, but it is already in use in several surgical specialties in both high-precision surgery and in standard surgical procedures. CAS has been used in neurosurgery since the late 1980s for treatment of tumours and vascular malformations.\textsuperscript{30} The neurosurgeons use the 3D model of the brain to safely and precisely navigate and treat different lesions. Before the introduction of CAS, many tumours were seen as inoperable because of their location and the large incisions and openings of the skull that were often needed. Robotic technology has allowed a great development in neuro-microsurgery, compensating for the surgeon’s physiological tremor with increase of accuracy. CAS is also used in otorhinolaryngology surgery and commonly involves navigation for locating and avoiding important anatomical structures, such as the optical nerve and the brain in endoscopic sinus surgery.\textsuperscript{31} Furthermore, CAS plays an important role in orthopaedic surgery, visceral surgery and different kinds of cardiac interventions.\textsuperscript{32}

1.3 A description of the work-flow for virtual planning in CMF

The different steps in virtual planning are dependent on the specific application, e.g., orthognathic surgery, CMF reconstruction, trauma, dental- or craniofacial implants, but a typical work flow consists of the following steps:

1. Data acquisition (CT/CBCT, intraoral scanning, 3D photos).
2. Image processing including segmentation.
3. Preoperative planning and virtual surgery.
5. Guide/template/PSI manufacturing via RP.

Depending on the complexity of the case, intraoperative navigation and final confirmation with an intraoperative CT may be an addition to the presented algorithm. Figure 1 shows an example of a standard workflow for a commercial available VSP system.
The image data is imported in a Digital Imaging and Communication in Medicine (DICOM) format into a VSP software. This can be a commercial software, such as Materialise \textsuperscript{33}, Planmeca \textsuperscript{34} or Brainlab. \textsuperscript{35} The planning may be based on the communication with a computer engineer or via an in-house solution where the surgeon performs all the relevant processing and analysis steps in the workflow. Before the planning and simulation can start, it is important to perform different kinds of image processing steps, including reorientation of the CT data, segmentation of the anatomical structures of interest (e.g., skull, mandible, teeth, soft tissue, nerves and vessels).

In planning for orthognathic surgery, the next step is to create a composite model of the skull with all necessary information. Currently, none of the existing CMF imaging techniques can capture a competent 3D model of all structures (e.g., facial skeleton, dentition and soft tissue) with the quality required. Hence, there is often a need for combining and merging different 3D imaging techniques. The virtual model of the skull can then be used to simulate surgical situations and perform measurements. The pre-processing steps and merging of different imaging sources are normally performed by a computer engineer/scientist and need to be approved by the surgeon before the relevant guide or implant can be designed and manufactured. It is a sub-
stantial challenge to have an efficient work-flow and communication in VSP. Likewise, it is crucial to develop a fast and reliable protocol given the greater urgency often required when working with trauma and oncological cases. The costs for using VSP are significant, both when done with an external partner, as well as investing in and maintaining an in-house setup. This concerns investments into software, hardware for production of models, guides and patient-specific implants (PSI). However, improved surgical outcomes will affect cost considerations, which is discussed in paper V.
2. Pre-operative management

This chapter discusses the different pre-processing steps and techniques in VSP, including image acquisition with CT/CBCT, intraoral scanning, segmentation, image registration and haptic technology.

2.1 Image acquisition

Image resolution is the core of an accurate model for virtual planning. No image-processing step can compensate for insufficient resolution in the original data. Historically, the CMF region and the facial relationships have been studied using different kinds of two dimensional (2D) radiograph techniques; panoramic images, lateral cephalometric and posterior-anterior (PA) views. These radiographs provide a reliable overview of the regions of interest and are still useful in many areas of CMF-surgery and in the field of dentistry. However, the images have a limited resolution and are sometimes difficult to interpret due to overlaying air, soft tissue and ghost images. 2D cephalometric analysis remains the gold standard in the planning of orthognathic surgery in many CMF-clinics, allowing comparison with normative data and prediction of the surgery.

![Figure 2. Pre- and postoperative x-rays of an orthognathic case in a lateral cephalometric view. Consent for publishing obtained from patient.](image-url)
Figure 2 shows pre- and postoperative 2D lateral cephalometric radiographs of an orthognathic surgery case. In less complex cases, 2D visualisations can be sufficient. However, when it comes to more complex surgical planning and the desire to use virtual planning techniques, there is a need to provide the facial skeleton in a 3D view.

Recent improvements of image quality and resolution in CT scans can now provide images with a slice thickness of less than 0.5 mm. Today CT is an invaluable imaging tool in the diagnosis and planning of diseases and deformities in the head and neck region. The CT image is based on grayscale values and built up of a high number of 3D pixels, voxels, as seen in Figure 3.

**Figure 3.** Pixel versus voxel. Figure provided by Lene Arensdorff Kristiansen.

Different tissue types will absorb radiation to various degrees based on the radio-density in the tissue. Each voxel in the CT image represents a value dependent on the radio-density. This value is given in Hounsfield units (HU), where water corresponds to a value of 0, air to -1000, while bone ranges from 400-3000 dependent on its density. Table 1.
Table 1. Approximate Hounsfield unit (HU) values for different types of tissue

<table>
<thead>
<tr>
<th>Tissue</th>
<th>HU</th>
</tr>
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<tr>
<td>Air</td>
<td>-1000</td>
</tr>
<tr>
<td>Water</td>
<td>0</td>
</tr>
<tr>
<td>Soft tissue</td>
<td>10 to 60</td>
</tr>
<tr>
<td>Soft tissue (contrast)</td>
<td>100 to 300</td>
</tr>
<tr>
<td>Bone</td>
<td>400 to 300</td>
</tr>
</tbody>
</table>

The size of the voxel in the CT image can be isotropic (uniform) or anisotropic (non-uniform) Figure 4. Anisotropic voxels are normally used in CT-images in medicine where the voxel size in x and y is constant, 0.3-0.5 mm, and z can differ depending on both slice thickness and pixel spacing.

Figure 4. Isotropic (uniform voxel; left) and anisotropic (non-uniform; right).

A voxel in the CT-image can often cover more than one tissue type, e.g., bone and soft tissue. A voxel in the transition line is assigned the average HU-value of the two tissue types, resulting in a blurred boundary between tissue regions. This phenomenon is also known as the partial volume effect (PVE). This is particularly discussed in the field of visualisation of the orbit, where the bony walls can be thinner than the actual voxel size, resulting in so-called pseudo holes caused by the PVE. Other artefacts seen in CT images are intensity noise, streak artefacts from metallic objects and motion artefacts due to patient movement during the scanning. Figure 5 illustrates the problems with metal artefacts from dental restorations.
The CT technique produces high quality images of the complete head and neck area in a few seconds. However, the dose of radiation should not be neglected. The introduction of Cone Beam Computed Tomography (CBCT) has opened up for new possibilities in the field of CMF. CBCT can provide high quality information of the entire CMF area with considerably less radiation to the patient. Another advantage of the CBCT in comparison to the conventional CT is that the image is captured with the patient in an upright position. This prevents distortion of facial soft tissue that occurs when the patient is supine. The fairly low cost of CBCT is also contributing to its increased clinical use. However, CBCT is more challenging to visualise and analyse since the grayscale values do not represent actual HU values and the frequency of scatter artefacts is higher in the CBCT. Images from both CT and CBCT are stored using DICOM format. The main technical difference between the CT and CBCT is the shape of the X-ray beam(s). CT-scans rely on fan-shaped X-ray beams with several detectors arranged in an arc around the patient. In CBCT, the X-ray source and the detector panel rotate around the patient. The beams diverge into a cone structure and the image is normally achieved in a single rotation.

Currently, advanced 3D imaging techniques are available that can display separate parts of the facial structures with high accuracy. However, none of the present CMF imaging techniques can capture a 3D-model with adequate quality.

Generally, there are two ways to produce an accurate digital 3D model of the dentition. The first method is via an indirect technique, where the traditional plaster models are imaged with a laser scanner or with high resolution CT/CBCT. The second way is via a direct technique, using an intraoral opti-
ical scanner, without the need for any traditional impressions and plaster cast models.

Accurate representation of the exterior soft tissue profile is of high interest in treatment planning and evaluation in orthognathic surgery. The facial external soft tissue can be recorded through a laser scanning technique or via different types of optical techniques (3D photography). 41, 42 These techniques capture the surface of an object and do not provide any harmful radiation to the patient. The digital image of the facial soft tissue can then be integrated into the CT/CBCT data of the bony structures to predict the soft tissue changes and allow for evaluation in orthognathic surgery. 43

2.2 Pre-processing and segmentation

Before the planning and simulation can start, it is important to perform different kinds of image processing steps, including reorientation of the CT data and segmentation of the anatomical structures of interest (e.g., skull, mandible, teeth, soft tissue, nerves, vessels). Analysis and simulation in 3D starts with the creation of a surface model of the bony structures via segmentation. Image segmentation is the process of dividing a digital image into multiple segments. The goal of segmentation is to simplify and change the representation of an image into something that is more meaningful and easier to analyse. The segmentation process is based on assigning a label to every voxel in an image. This results in voxels with the same labels sharing visual characteristics. The simplest method for image segmentation is based on the selection of threshold values. 44 This is done by selecting all voxels above or below a certain intensity threshold. In CT images, the HU scale can be a guideline to select thresholds that will separate different tissue types from each other. The threshold difference between bone and soft tissue can, however, be very small, making it difficult for the computer to automatically perform the separation between the two types of tissue. This is a particular problem when performing segmentation in areas with thin bones or bones with low radio-density.

Currently, the segmentation is often performed by computer engineers/scientists who manually trace the contours of the bone structures in each slice in the 3D image. Manual segmentation is known to be accurate but time-consuming and tedious. The increased interest to integrate virtual planning in the everyday workflow has led to the development of semi-automatic and more intuitive segmentation methods. Those methods use different algorithms so that the surgeon can perform the segmentation process in a faster, more efficient, in-house set-up. 12, 45
2.3 Image registration

Image registration is the process of transforming different sets of image data into one coordinate system. Registration is necessary in order to be able to compare or merge data obtained from different image modalities or different time points. This can be done by either manually placing corresponding landmarks on the objects or by using an iterative closest point (ICP) algorithm. The algorithm is employed to minimise the distance between two surface models. \(^{46}\) ICP registration requires both a reference surface and a source surface. A reference surface can be a whole surface or a specific region of interest. The first step in the registration procedure is to manually align the two surfaces. Subsequently, the software uses the ICP algorithm to calculate the rotation and translation between two data sets and align the two surfaces automatically. This algorithm is designed to minimize the difference between two clouds of points. In the process, one point cloud, the reference, is kept fixed, while the other one, the surface to be aligned, is transformed and rotated to best match the reference.

![Image of registration using ICP algorithm. Orbits before and after surgery are registered to compare the difference in shape between the two models.](image)

2.4 Haptic technology

Haptic technology regenerates the sense of touch by transmitting a force or vibration back to the user in a virtual environment. It is used to improve the realism in simulators and is already available in training for specific surgical procedures. \(^{47}\) Haptic has the potential to simplify preoperative planning by giving the surgeon virtual tools that are familiar from the operation theatre, namely, that the surgeon can get a sensation of the fit of two bone fragments or the occlusion. The sense of touch (haptics) is an essential supplement to the visual perception. A haptic device is normally built as a stylus or a ball attached to a robot arm. Most devices use kinaesthetic feedback, i.e. a direction force back to the user holding the stylus or the ball. Haptic devices can
also give a tactile feedback, which refers to a sensation felt by the skin, for example a vibration or texture. In this thesis, we have worked with a PHANTOM Desktop haptic device (Figure 7) from Sensable Technologies.

*Figure 7. Haptic device with stylus attached to a robot arm.*
3. Aims

The overall aim of these five studies was to develop and evaluate new virtual planning tools for CMF-surgery and to investigate their usefulness in a clinical set-up.

I, II. The aim of study I and II was to establish and evaluate a method to create a composite 3D model of the facial skeleton and the dentition with high accuracy. Another goal was to adopt intraoral digital scanning for virtual bite registration in centric relation (CR) without the need of traditional plaster casts and model surgery.

III. The aims of this study were to introduce a new approach for semi-automatic segmentation and shape analysis of the orbit, and to investigate the usefulness of the software by determining the intra- and interobserver variability.

IV. The aims of this study were to describe a new workflow for virtual reduction of complex mandible fractures and to investigate the usefulness, the accuracy and reproducibility of the virtual tool, HASP.

V. The aim of this systematic review was to determine if virtual planning has an influence on the duration of the surgery compared to the traditional free-hand approach. In addition, we sought to screen the literature for other factors regarding time differences between the virtual surgical planning (VSP) and the conventional planning strategies; e.g., preoperative planning time, ischemia time and hospitalization.
4. Introduction to the studies included in the thesis.

This chapter provides background information on the different topics discussed in the five studies included in this thesis.

4.1 Introduction to paper I and II – Development of a workflow for virtual bite registration.

4.1.1 Orthognathic surgery

Orthognathic surgery is defined as the surgical manipulation of parts of the facial skeleton to realign and correct a dentofacial deformity into an anatomical and functional relationship. The surgery is a standard procedure in the field of oral and maxillofacial surgery and can be used to manage a broad spectrum of maxillofacial abnormalities, including congenital, developmental, and acquired.\(^{48,49}\) The treatment is a combination of surgery and orthodontics and the goal is to achieve a functional dental occlusion, meaning an optimised way for the teeth in the upper and lower jaw to meet.

The study of the dental occlusion is a key-planning step in orthognathic surgery.\(^{14,50}\) A traditional workflow is based on impression taking, wax bite registration, face bow transfer, plaster cast modelling and mounting the cast in an articulator made in parallel with radiological assessment. This is a time-consuming procedure that requires much laboratory work.\(^{51,52}\) In addition, possible inaccuracies of each step will be transferred to, and will be amplified in the following step.\(^{53,54}\) With the new digital techniques available, there is a potential to replace the traditional plaster models, allowing new options for occlusal analysis and treatment workflows. Based on these digital workflows, physical guides can be produced, using rapid prototyping technologies, to translate the digital plan into the operation theatre.\(^{15}\) However, surgical planning requires a model of adequate precision to enable a satisfactory outcome in the actual surgery. Inaccurate models may lead to false information and incorrect treatment outcomes.

CT and CBCT are both considered being viable image modalities for the 3D visualization and analysis of bone in the maxillofacial region.\(^{38,55-57}\) They
offer the possibility for a 3D model to be created. However, limited image resolution, creation of metal artefacts and difficult image segmentation and separation of the upper from the lower teeth inhibit accurate 3D modelling and visualization of the teeth. Additionally, the orthognathic patient is often scanned with the teeth in a closed, habitual position but not in the diagnostic, centric relation (CR) that is required for treatment planning.

### 4.1.2 Intraoral scanning

Computer modelling of the dental occlusion requires a precise image technique. In recent times, there has been a growing interest in the clinical application of intraoral scanning (IOS) techniques with particular reference to image capture of the dental occlusion. IOS makes it possible to visualize the surface of the teeth with a resolution that approaches microns. In addition, it creates no interaction with metal objects and causes no harmful radiation to the patient. There is a constant development in the field of IOS, covering the spectrum from monochromatic image acquisition with coating to advanced video acquisition with colour and without the need of additional coating. The scanners are based on optical principles and allow certain points to be identified on an object’s surface. Image processing software is then used to create a surface mesh from these points. The quality of IOS is progressively improving, and they are becoming easier and more reliable to operate. The use for IOS in the field of prosthodontics is already well-established and excellent accuracy and precision in single-unit scan has been demonstrated. The development of IOS techniques has now improved to the point where they can obtain image information of a full arch with high accuracy. However, it needs to be highlighted that these are results from in vitro studies. The question remains of how feasible these techniques are in the clinical application. Additional errors such as patient movement, saliva, and space limitations in the patient’s mouth may negatively influence the accuracy of the digital impression. Figure 8. There is still more research and evaluation that needs to be done in the field of full arch scans with IOS, but the rapid development is opening up for new applications in the field of dentistry and maxillofacial surgery.
Figure 8. Example of space limitation when scanning the posterior sites of the dental arches.

4.1.3 Bite registration
The success of orthognathic surgery relies on the surgical performance by the surgeon, but is also highly dependent on the creation of a precise surgical plan. The preoperative orthodontic treatment often includes greater movements of the teeth to prepare for the new, planned position of the jaws. Due to this reason, the patient does not have a repeatable habitual occlusion. During surgical planning, the bite registration must be captured in centric relation (CR) since this is the only reproducible, stable position for the lower jaw. Failure to perform a bite registration in CR will lead to an unwanted post-operative result or an inaccurate plan. 53

4.2 Introduction to paper III – a semi-automatic segmentation method for orbital volume and shape-analysis.

4.2.1 The orbit
The eye-socket, or orbit, is shaped like a pyramid and built up by parts of seven different bones, Figure 9. The function of the orbit is to support and protect the eye and surrounding tissue. The rim of the orbit is rectangular in shape with rounded corners and formed by thick cortical bone that provides a stable buttress for the craniofacial skeleton. The inner walls are thin, especially in the floor and in the medial wall (lamina papyracea). The thickness in these two areas can be down to 0.3 mm. The lateral wall and roof are
made of thicker bone and are less commonly involved in fractures of the orbit. In all of the four orbital walls, openings are present for passage of highly important vessels and nerves. There are seven muscles inside the orbit: superior, inferior, lateral and medial rectus muscle, superior and inferior oblique muscle and levator palpebrae muscle, figure 10.

4.2.2 Orbital fractures

Orbital fractures are one of the most common fractures in the midface. Reconstruction of the orbital walls is highly challenging due to its complex 3D anatomy.\textsuperscript{67} Fractures of the orbit can be divided into pure orbital fractures, also commonly described as blow out fractures. These types of fractures only involve the internal orbital walls. Pure orbital fractures occur in the inferior and/or medial wall where the bone is thinnest. The other fracture type is the impure orbital fracture, which also include a fracture of the orbital rim. Figure 11 shows an example of a pure orbital fracture in the inferior wall.

Fractures involving the orbit can lead to a change in orbital volume and alter the position of the eye. The goal of treatment of orbital fractures is to prevent early complications, such as vision loss or oculocardiac reflex due to muscle entrapment, but also to minimize the risk for late complications like diplopia (double vision) and malposition of the globe.\textsuperscript{68} Fractured and unstable areas need to be bridged by implants or bone grafts in order to support the orbital content and to re-establish the original anatomy. The unique and complex anatomy of the orbit requires accurate and precise contouring of the orbital...
mesh or graft to restore the proper shape and volume of the orbit. A fracture of the orbital walls often results in a comminute fracture with displaced bone pieces and the goal of the surgical treatment is to reconstruct the whole displaced bone areas rather than repositioning and fixating existing fragments.

Figure 11. Pure orbital fracture in the right, inferior orbital wall. (A) Coronal CT view of the fracture. (B) 3D surface visualisation of the same case.

4.2.3 Orbital imaging and segmentation
The benefits of preoperative planning cannot be overestimated in orbital reconstructive surgery. $^{69, 70}$ CT scans with thin slices are the gold standard to detect and evaluate orbital fractures. The coronal view is preferred to detect fractures of the inferior wall. Medial wall fractures are best visualised in the axial view. A soft tissue window can help determine muscle impingement. The development and routine application for CT processed within available software solutions has significantly simplified diagnosis, analysis and preoperative planning of orbital fractures. Of interest in surgical planning for orbital trauma is to measure the shape and volume, comparing pre- and postoperative results. This can be analysed in CT images, but requires precise segmentation of the orbit. A certain amount of volume change itself is not a sole indicator for surgery, but can be part of the overall assessment together with clinical findings and patient symptoms. $^{68, 71}$

Orbital imaging and segmentation is challenging due to the anatomical location and the thin nature of the bony walls. As discussed in the introduction, the partial volume effect (PVE) impacts the ability to achieve an accurate visualisation and representation of the walls. As a result of limited resolution in the CT data, the HU values of the thin orbital walls often overlap with the HU values of the soft tissue, resulting in pseudo holes and lost information in the segmented walls. Figure 12 presents an example of the PVE. Intensity noise, metal artefacts and artefacts due to patient movement, are other factors commonly blurring the image.
After the segmentation is performed, volume and shape of the orbit can be analysed. The intact side can be compared to the contralateral, fractured orbit and serves as a reference to analyse the shape in the preoperative assessment, but also as an evaluation after the surgery. This can be done by mirroring the intact side and performing a superimposition between the two orbits to visualise the agreement.

When virtual preoperative planning is discussed in the field of trauma, there is a need for a fast and user-friendly method to be used. Manual segmentation is considered the gold standard in terms of accuracy, but is time-consuming and sensitive to operator errors and therefore not viable in the everyday workflow for the surgeon. In this project, we are describing a semi-automatic method for orbit segmentation, where the surgeon can guide the segmentation process in an in-house software solution.
4.3 Introduction to paper IV – Haptic assisted virtual planning for complex mandibular fractures

4.3.1 Mandible fractures

Mandible fractures are one of the most common fracture types in the facial area, often resulting from traffic accidents, sports injuries or assault. Mandible fractures represent 36-70% of all facial fractures. This high percentage can be explained by its prominent position in the face and the relative lack of support. More mandible fractures can be seen in men, especially in the age group 20-30, where assault and motor vehicle accidents are the primary cause. The mechanism of the injury is important to take into account since this will give the surgeon an indication of the extent of the trauma and if any concomitant injuries are present. High velocity trauma like traffic accidents or gunshot wounds are more destructive to the craniofacial skeleton resulting in a higher degree of bony fragmentation and may often result in volume loss of the surrounding soft-tissue.

The mandible is U-shaped and is strongest in the midline (the symphysis) and weakest at both ends (the condyles). The condylar fracture is therefore the most common location, since the force of impact is transmitted from the body of the mandible and breaks it at its weakest point. A trauma to the ipsilateral side of the mandibular body often results in a contralateral fracture in the condylar region. Figure 13 shows an overview of the frequency of fractures at different locations.
There are muscle attachments along the entire course of the mandible that place dynamic vectors of force on the mandible. All these muscles serve an important role in maintaining proper mandible function. However, when in discontinuity, such as caused by a mandible fracture, a large displacement is not uncommon and can jeopardise fracture healing. The effect of muscle force on the fracture segments is important in evaluation of mandible fractures, especially the mandibular body or angle. They can be classified as favourable or unfavourable depending on whether the muscles serve to stabilise or displace the fracture segments. Figure 14 shows an example of a favourable and an unfavourable fracture.
The indication for open versus closed reduction of mandible fractures has changed dramatically over the last century. With the ability of treating fractures with open reduction and rigid internal fixation (ORIF), patients no longer require long periods with immobilisation and maxillomandibular fixation (MMF) for adequate healing. The decision-making of the treatment strategy for mandible fractures is dependent on the location, the degree of displacement and on whether the fracture affects the occlusion. 73, 75, 78 Favourable fractures, without displacement and malocclusion are normally treated conservatively, while displaced and/or multiple fractures with malocclusion often need ORIF with different types of osteosynthesis materials. For most of the mandible fractures, the treatment strategy is relatively straightforward. However, when it comes to more complex fractures with multiple segments, re-establishing of the three-dimensional shape of the mandible can be very challenging. This is especially the case for treatment of severely atrophic and edentulous mandibles. 79
Resorption of the alveolar process is a natural, progressive event after loss of teeth. In a severely atrophic mandible, even significant minor trauma can cause a fracture. Several factors make surgery with edentulous/atrophic mandible challenging. As mentioned, there is a lack of bone, and the existing bone is generally cortical, resulting in a lower healing potential due to a decreased blood supply. Since the patient is edentulous, there are no teeth present to help guide the reduction. If the patient’s general medical status allows for treatment in general anaesthesia, ORIF with long load-bearing osteosynthesis has significant advantages for these patients. The surgery also often includes immediate bone grafting to extend the stability in the fracture area. VSP, including pre-contouring of the plate or creating a patient-specific plate from an exact model of the patient’s mandible, could lead to a more accurate result and greatly decreased surgical time. Patients with atrophic and edentulous mandibles are mainly found among the geriatric population, where comorbidities often are present and where the total time under general anaesthesia has a strong impact on the overall morbidity.49

Successful treatment of complex mandibular fractures is dependent on careful consideration regarding the degree of displacement and loss of bone to accurately restore the occlusion and the original facial anatomy. The challenges include firstly achieving an accurate reduction of multiple fragments and secondly fitting a stable plate to re-establish the original shape of the mandible. The reduction and the adaption of the plate is a manoeuvre that
can require significant time even for the more experienced surgeon. Furthermore, these robust load-bearing plates needs to be accurately adapted to not cause malreduction and incorrect displacement of the condyle out of the glenoid fossa. An imperfect adapted plate can also be palpable through the skin and cause patient discomfort and result in a second surgery for plate removal.

VSP is already well established in orthognathic surgery and reconstructive CMF surgery. The advantages of VSP are presented in the literature and show both higher accuracy, shorter time spent in surgery and reduced intraoperative bleeding. There is also potential that VSP can be essential in diagnostics and treatment of complex fractures of the mandible, facilitating reduction and osteosynthesis.

Current commercially available VSP solutions for CMF are based on outsourcing the segmentation, planning and printing of relevant guides and implants to a computer engineer. This set-up is often expensive, and it may take up to two to three weeks for the guides or implants to be delivered. In both trauma and reconstruction for oncological reasons, the time for planning is very limited, which is often a problem in the traditional setup with existing planning systems. Virtual planning in the field of trauma needs to be fast and user-friendly. Another disadvantage with existing VSP systems is that they are primarily relying on two-dimensional graphical interfaces. This requires the user to visualize complex 3D anatomical structures from a two-dimensional view.

### 4.3.2 In-house virtual surgical planning including haptic technology

In collaboration with the Centre for Image Analysis at Uppsala University, a new tool for virtual reduction of mandible fractures has been developed. Haptic Assisted Surgical Planning (HASP) is an intuitive, in-house solution designed for the surgeon to perform all steps involved in both planning and evaluation.

HASP uses stereo graphics, six degrees-of-freedom (DOF) input, and haptic feedback to improve the surgical planning by allowing easier interaction with 3D data, figure 16. As part of the procedure, the surgeon manipulates virtual bone fragments in 3D through a haptic device, which provides 6DOF input and 3DOF force feedback. The haptic simulation computes a collision response when bone fragments collide, allowing the surgeon to assess the fit between bone fragments and to test whether the occlusion is correct. The haptic simulation also helps to avoid interpenetration of fragments that may be impossible to detect visually. Head-tracked stereo glasses allow the surgeon to receive correct depth perception and enable him/her to look around
in the virtual scene. Further details about the HASP system are provided in Olsson et al.\textsuperscript{12}

![Image of HASP hardware and a trauma case visualised in HASP.](image_url)

*Figure 16. HASP hardware including haptic device and head-tracked stereo glasses (left). A trauma case visualised in HASP (right).*

### 4.3.3 In-house 3D printing

The goal with VSP for complex mandible fractures is to perform virtual reduction to create a model as close to the original shape of the mandible as possible. The model can be manufactured through rapid prototyping (RP) in a 3D printer available at the clinic. The printed model can then be used for either pre-shaping the osteosynthesis material or for the manufacturing of a patient-specific plate. The ultimate goal for this is of course a workflow also including the possibility to fabricate PSI:s from metal for the individual osteosynthesis of the trauma patient, but regulatory issues, cost-effectiveness for caregivers and other infrastructural support are obvious problems to be solved.\textsuperscript{82}

For the individual patient with a complex mandible fracture, accurate virtual preoperative planning has the potential to shorten the operation time and improve the aesthetic outcome and function.

### 3.4 Time differences between VSP and conventional planning – a systematic review and meta-analysis.

The purpose of VSP and CAS technologies in CMF surgery is to increase precision and to reduce morbidity and operative time.\textsuperscript{1, 83} Computer assisted planning is used in a broad area of CMF surgery and the advantages have been described in a number of studies.\textsuperscript{6, 21, 84-86} Despite the large quantity of published studies focusing on the benefits of VSP, the question if it decreas-
es time spent in surgery has still not been fully answered. A reduced time in the operating theatre could potentially lead to a better outcome for the patient and at the same time decrease the overall cost. Hence, a decreased operative time, ischemia time and hospitalization could thereby, potentially, justify the additional preoperative costs that come with computer assisted surgical planning.
5. Material and Methods

This section discusses the methodology used for the different studies, as well as considerations around inclusion/exclusion criteria, ethical approval and statistical analysis.

The expressions *accuracy* and *precision* are frequently used in this thesis. While their exact definition varies between studies in this field, for the purpose of this thesis, *accuracy* is defined as the ability of a measurement to match the actual value and *precision* is defined as the ability of a measurement to be consistently reproduced.

5.1 Paper I, II

Both papers were based on an experimental in vitro study on a plastic skull model with detailed dental surfaces. Orthodontic metal brackets with arch wires were applied on the buccal surface of the teeth to imitate a planning case for orthognathic surgery. The traditional steps for planning orthognathic surgery were performed, including the creation of alginate impressions of the upper and lower jaw, the fabrication of plaster cast models, the development of a standard wax bite where the mandible was positioned into a simulated CR, and finally a face bow registration. The casts were then mounted into an articulator and the occlusion pattern was registered. CT and CBCT scans were obtained scanning the skull in both a maximum intercuspation position (MIP) and also with the wax bite in place and the mandible positioned in CR. An intraoral scanner (IOS) was used to scan the dental surfaces and to perform a bite registration in CR using two different methods. The obtained wax bite in CR was used for both methods, figure 17. In the first virtual bite registration technique, the buccal surfaces of the model were scanned with the wax bite in situ. In the second method, the wax bite itself was scanned using the IOS. The accuracy of merging the digital impressions from the IOS with the CT and CBCT scans was evaluated by measuring the deviation between the objects. A colour coded distance map was used to visualise the accuracy.
Figure 17. Virtual bite registration. The yellow model represents the buccal scan technique. The green model represents the scanned wax bite.

The two different virtual bite registration techniques were evaluated by creating a duplicate of the lower jaw with the identical mesh structure. The copy was then moved away from its original position and thereafter repositioned with guidance of the two different virtual bite registration methods. This allowed an evaluation of the accuracy of the virtual bite registration by calculating the deviation between the “unmoved” original surface model of the lower jaw and the repositioned mandible, figure 18. A rotational axis was placed through the centre of the condylar head and the mandible was rotated into dental contact. The virtual contact pattern was compared with the conventional articulator model. The different imaging processing steps, segmentation and analysis were performed in Amira, (Amira Version 5.5.0, FEI Visualisation Sciences Group, Bordeaux, France), a commercial software package for image visualisation and data analysis.

Figure 18. The method used to evaluate the virtual bite registration technique.
Statistical Analysis
In this study, only descriptive statistics were reported (tabulated data, mean, median, max values and standard deviation).

Ethical approval
The ethics committee of Uppsala approved of the study design. (Dnr 2014/088)

5.2 Paper III
This study was intended to investigate the accuracy and precision of a semi-automatic segmentation method using a series of retrospective orbital trauma cases. Patients were enrolled through a search in the medical records of the Department of oral and maxillofacial surgery at Västerås hospital, Sweden, between 2012 and 2014. Patients were included if they had undergone a surgical reconstruction for a unilateral orbital fracture and if pre- and post-operative CT scans with sufficient quality were present. The maximum slice thickness of the CT scans was 1.5 mm for a patient to be included. 23 patients met the inclusion criteria and 21 patients gave their informed consent to participate in the study. The same surgeon treated all included patients and the surgeries were performed within 1-21 (mean 6.5) days after the injury.

5.2.1 The surgical procedure
The surgical approach was dependent on whether a laceration was present, and existing patient conditions, such as age. The most common approach was the subciliary, yet the subtarsal and infraorbital were also used. An overview of the surgical approaches is presented in figure 19. The fractured area was exposed and a combined mesh made of porous polyethylene and titanium (DePuy, Synthes, Johnsson & Johnsson, West Chester, PA, USA) was used. The implant was trimmed and adjusted to the fracture area to accurately cover the missing bone and to stabilize the orbital soft tissue.
Figure 19. Approaches through the external skin to the orbit. (A) Subciliary. (B) Subtarsal. (C) Infraorbital.

5.2.2 Segmentation and shape analysis
DICOM data from the retrospective cases was imported into the semi-automatic segmentation software, developed at the Centre for Image Analysis, Uppsala University, Sweden. The segmentation method is semi-automatic and uses a deformable surface model and 3D interaction with haptics. It consists of the following steps:

1. Segmentation of the orbital bones by Hounsfield unit (HU) thresholding.
2. Closing the anterior opening with a plane fitted to four user-selected landmarks.
3. Fitting of the deformable model into the orbit cavity enclosed by thresholded bones and the anterior plane.
Figure 20. Overview of the semi-automatic segmentation process. (A) Marking of the anterior opening of the orbit. (B) Initialization of a deformable model inside the orbit. (C) The model is fitted to the orbit using CT image information and haptic 3D user interaction.

Two observers performed the segmentation procedure twice each for all the cases. The inter- and intraobserver variability was evaluated. Quantitative and visual shape analyses of the segmented orbits were performed by mirroring the intact side on to the fractured side and calculating the deviation, surface distance and volume overlap, between the two models.

Statistical Analysis
Pre- and postoperative volume differences were compared using a Wilcoxon signed rank test. The precision of the segmentation method was analysed with Bland Altman plots.

Ethical approval
The ethics committee of Uppsala approved to the study design. (Dnr 2013/301)
5.3 Paper IV

This study was created to demonstrate a new workflow for an in-house VSP system for complex mandible fractures and to investigate the accuracy, precision and the time used for planning.

To evaluate the accuracy, we used a plastic skull model with detailed dental surfaces. The plastic skull was scanned with CT before a bilateral fracture was created on the model. A new CT scan was obtained and both scans were exported in DICOM format into BoneSplit for segmentation. BoneSplit is an interactive segmentation tool that uses a 3D texture-painting interface for bone separation. The semi-automatic segmentation in BoneSplit enables quick separation of individual bone fragments after an initial threshold value for bone tissue has been selected. A graph-based segmentation method is used to automatically compute a label image from seeds that the user paints on the surface of the bone.

The segmented data was imported into HASP and three different users performed the virtual reduction. All three users performed the planning twice. Accuracy was evaluated by comparing the virtual reduction with the intact skull model. Intra- and interobserver variability was evaluated.

The tool was also evaluated on a series of retrospective trauma cases with complex mandible fractures. The patients were identified through a search in the patient database at the department of Oral and Maxillofacial surgery at Uppsala University hospital between 2015 and 2017. Inclusion criteria were a mandible fracture with at least two displaced fractures with existing pre- and post-operative CT/CBCT scans with a slice thickness of less than 1 mm. The data was segmented in BoneSplit, and the virtual reduction was done in HASP by the same observers as for the plastic skull. The planning was performed twice to enable evaluation of both intra- and interobserver variability, described in mean absolute distance (MAD), maximum distance, volume overlap (DICE), and angular difference.

**Statistical Analysis**

Descriptive statistics were reported (tabulated data, mean absolute distance, max values and range).

The intra- and interobserver variability of the method was analysed with Bland Altman plots.

**Ethical approval**

The regional ethics committee of Uppsala approved of the study design (Dnr 2016/444).
5.4 Paper V

This systematic review followed the PRISMA Statement guidelines. For a study to be included, it was required to compare the time difference between surgery performed with aid of VSP and surgery with conventional planning/free hand approach. The review included data on all types of cranio-maxillofacial surgeries. Time data from both planning phase, operative time, ischemia time and hospitalization were recorded. Case reports, case series of less than 5 patients, animal studies, in vitro studies and review papers were excluded. Data regarding navigation was also excluded. The literature search was conducted using the medical subject heading (MeSH) terms and is described in full text in Appendix 1.

**Statistical Analysis**

Descriptive statistics were used to report the data. A meta-analysis was performed, evaluating the differences in operative time, ischemia time and hospitalization between the VSP group and the control group. The $I^2$ statistic was used to express the percentage of the total variation across studies based on heterogeneity, with 25% corresponding to low heterogeneity, 50% to moderate, and 75% to high. The inverse variance method was used for the random-effect model. A meta-analysis was attempted only if there were studies with similar comparisons reporting the same outcome measures, e.g., operative time, ischemia time and hospitalization. A funnel plot was drawn describing the effect size versus standard error. This could indicate potential publication bias and other biases related to sample size. The data was analysed in Review Manager (version 5.3.3, The Nordic Cochrane Centre, The Cochrane Collaboration, Copenhagen, Denmark, 2014).

**Ethical approval**

No ethical approval was needed
6. Results and Discussion

6.1 Paper I, II

Results
This study presented and evaluated a technical workflow for merging different 3D-data of the cranio-maxillofacial skeleton, dentition and how to virtually position the mandible in CR. The workflow involved image acquisition, CT/CBCT and intraoral scanning, and image processing, including image segmentation and registration. The study also demonstrated a method of creating an axis though the condylar heads to enable rotation of the mandible and the possibility to obtain a virtual occlusal contact pattern. The difference between the intraoral scanned imaged and the underlying CT and CBCT image is visualised in a color-coded distance map, figure 21. The mean absolute distance of the two surface models was below 0.2 mm for both CT and CBCT. Table 2 shows the differences in the distance between the overlapping surface models of CT/CBCT and intraoral optical scanning. The maximum deviation was seen in the posterior region and around the orthodontic brackets.

Virtual bite registration into CR was evaluated by two different approaches and the buccal scanning technique showed superior results compared to the virtualised wax bite technique. Table 3 presents the differences in distance between the lower jaw positioned with guidance of the two different virtual bite registration approaches.
Figure 21. The accuracy of merging the digital impression of the dentition from an intraoral scanner and the underlying CT/CBCT model is represented with a colour coded distance map.

Table 2. Differences in distance (mm) between the mesh overlap following the registration of CT/CBCT data and surface data from intraoral scanning.

<table>
<thead>
<tr>
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<th>Mean</th>
<th>SD</th>
<th>Median</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT maxillary arch</td>
<td>0.15</td>
<td>0.12</td>
<td>0.13</td>
<td>0.99</td>
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<tr>
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<td>0.13</td>
<td>0.15</td>
<td>0.93</td>
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<tr>
<td>CBCT mandibular arch</td>
<td>0.17</td>
<td>0.13</td>
<td>0.14</td>
<td>0.87</td>
</tr>
</tbody>
</table>
Table 3. Difference in distance (mm) between the lower jaw, positioned with guidance of the two different virtual bite registration approaches using the unmoved lower jaw as a reference.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
<th>Median</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT buccal 1</td>
<td>0.41</td>
<td>0.077</td>
<td>0.37</td>
<td>0.69</td>
</tr>
<tr>
<td>CT buccal 2</td>
<td>0.41</td>
<td>0.13</td>
<td>0.39</td>
<td>0.73</td>
</tr>
<tr>
<td>CT wax bite scan 1</td>
<td>1.3</td>
<td>0.32</td>
<td>1.3</td>
<td>1.8</td>
</tr>
<tr>
<td>CT wax bite scan 2</td>
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<td>0.23</td>
<td>1.0</td>
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<tr>
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<tr>
<td>CBCT buccal 2</td>
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<tr>
<td>CBCT wax bite scan 2</td>
<td>1.0</td>
<td>0.30</td>
<td>0.69</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Discussion

This study demonstrates the technical workflow, including imaging processing steps, to create a composite model for orthognathic surgery planning. Our main observation was that there was no possible way to create an accurate 3D model for orthognathic surgery planning using just one single image modality. Additionally, we observed a lack of CR consideration in the existing computer-assisted planning. Hence, there was a need for the merging of different imaging modalities, as well as to evaluate the accuracy of the registration between different sources. An alternative to the two virtual bite registration approaches described in this study is to achieve the CBCT scanning with the patient positioned in CR with the aid of a wax bite. This would also facilitate the segmentation and separation of the upper from the lower jaw. The virtual bite registration using an intraoral scanner on the other hand, offers the option to relocate a 3D model of the lower jaw at any assessment of the treatment stage using both CT and CBCT scans.

Centric relation (CR) describes the jaw relationship between the maxilla and the mandible when the mandible is in its most retruded position. This is done by gently manipulating the mandible backwards and upwards. CR is the most reproducible jaw relationship and is an important corner stone in prosthodontics and also in orthognathic surgery. Xia et al68, discussed this topic in the light of orthognathic surgery, describing the importance of bite registration in CR and how failure to capture the accurate occlusion in CR can cause either an unwanted outcome or an inaccurate plan. They also state that bite registration in CR serves as a reference and foundation for the entire process of orthognathic surgery. A failure to properly reposition the mandibular condyles during a mandibular orthognathic surgical procedure has been widely studied in the literature, as it will negatively affect the outcome and
occlusion and therefore represents a very important technical step in the surgery.91

The traditional planning setup, with plaster cast models mounted on an articulator, assists the surgeon in the preoperative assessment. However, these casts limit the analysis to the dental surfaces and interocclusal relationship. The impact on the movements on the facial bone and soft tissue cannot be evaluated simultaneously. Another disadvantage is the amount of time spent on laboratory work. Steinhuber et al52 and Wrzosek et al51 reported on the difference in preoperative planning time for orthognathic surgery, comparing computer-assisted 3D planning and conventional planning. Both studies showed a significant difference in time spent, with 3D planning taking considerably less time. The most obvious time saving was seen in the laboratory work.

It is important to note, that when comparing different models from different image modalities, it is only possible to show the deviation between the nearest neighbouring surface points. This can introduce inaccuracies in the result, because the distance may be calculated in different directions, providing different results depending on which surface is defined as the reference surface. When calculating the distance between two exact 3D copies, however, which in this case was the position and repositioning of the 3D mandible models, we were able to analyse the deviation between the exact matching mesh points and therefore do not encounter this problem. This representation is closer to a true measurement and therefore will create other types of 3D colour-coded distance maps. We were able to apply the mapping technique onto two identical 3D models with identically numbered and located mesh points.

There is still more research and evaluation that needs to be done in the field of full arch scans with IOS, but the rapid development is opening up for new applications in the field of dentistry and maxillofacial surgery. The limits for the use of IOS may be expanding and an interesting field of scanning intraoral soft tissue would be a next valuable step to explore. Olsson et al92, presented a novel method of haptic-assisted surgical planning aiming to predict and match the recipient soft tissue defect with the soft tissue flap. The study describes both the concept of planning the osseous component but also a way of predicting the size and location of the vessels of the skin paddle.

In summary, this study describes a new method for virtual bite registration using intra oral scanning and CT/CBCT in order to create a composite 3D model of the craniomaxillofacial region without the need for any additional laboratory work. The method suggests the use of intraoral scanning to first capture the detailed morphology of the teeth, followed by a scan of the buc-
cal surfaces with the mandible placed in CR. An accurate 3D model was created and can be used for orthognathic surgery planning. Further studies to implement these results in a clinical setup are needed and should be part of the ongoing research agenda.

6.2 Paper III

Results

There was a statistically significant orbital volume difference (p<0.01) before and after a surgery. The mean volume of the intact orbit was $27.2 \pm 2.8$ ml. The pre-operative mean volume difference was $1.3 \pm 1.1$ ml, while the post-operative mean volume difference was $0.9 \pm 0.6$ ml. The precision analysis of the segmentation system, described by intra- and interobserver variability, is presented in figure 22. The estimated time for performing the semi-automatic segmentations was between 5-10 min for each orbit. Table 4 summarises the results of the quantitative shape analysis, presented in mean absolute distance (MAD), maximum absolute distance (Hausdorff) and the volume overlap (Dice similarity coefficient), between the mirrored fractured orbit and the contralateral orbit. Figure 23 demonstrates a case before surgery, superimposing the fractured, mirrored orbit on the intact contralateral orbit and visualising the shape differences. Figure 24 demonstrates the same case after surgery.

Table 4. Preoperative and postoperative data in study subjects. **DSC**: Dice similarity coefficient. **Max**: maximum. **Abs**: absolute. **Post-op**: postoperatively. **Pre-op**: preoperatively. Figures in parentheses denote standard deviation.

<table>
<thead>
<tr>
<th>User</th>
<th>Mean abs. distance (mm), pre-op</th>
<th>Mean abs. distance (mm), post-op</th>
<th>Max abs. distance (mm), pre-op</th>
<th>Max abs. distance (mm), post-op</th>
<th>Volume overlap (DSC), pre-op</th>
<th>Volume overlap (DSC), post-op</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1T1</td>
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<td>0.553 (0.140)</td>
<td>5.019 (1.922)</td>
<td>3.986 (1.663)</td>
<td>0.930 (0.020)</td>
<td>0.948 (0.013)</td>
</tr>
<tr>
<td>U1T2</td>
<td>0.791 (0.244)</td>
<td>0.587 (0.120)</td>
<td>5.383 (2.210)</td>
<td>4.120 (1.511)</td>
<td>0.919 (0.025)</td>
<td>0.940 (0.012)</td>
</tr>
<tr>
<td>U2T1</td>
<td>0.782 (0.252)</td>
<td>0.574 (0.152)</td>
<td>5.037 (2.382)</td>
<td>3.804 (1.691)</td>
<td>0.925 (0.024)</td>
<td>0.946 (0.014)</td>
</tr>
<tr>
<td>U2T2</td>
<td>0.721 (0.224)</td>
<td>0.568 (0.133)</td>
<td>4.976 (2.189)</td>
<td>4.096 (1.534)</td>
<td>0.930 (0.022)</td>
<td>0.945 (0.013)</td>
</tr>
<tr>
<td>Total</td>
<td>0.756 (0.232)</td>
<td>0.570 (0.135)</td>
<td>5.104 (2.148)</td>
<td>4.001 (1.578)</td>
<td>0.926 (0.023)</td>
<td>0.944 (0.013)</td>
</tr>
</tbody>
</table>
Figure 22. Bland-Altman plots showing the inter-observer (A, B) and intra-observer (C, D) variability of the semi-automatic orbit segmentations.
Figure 23. Preoperative shape comparison between a fractured orbit (red) and the mirrored contralateral side (blue). Semi-transparent overlays in column 3 display the spatial overlap between the orbits, whereas the color-coded distance map in columns 4 and 5 show the signed and unsigned surface-to-surface distance, respectively.

Figure 24. Corresponding comparison of the orbit shapes after surgery.
Discussion
The study showed that the average volume overlap (DICE) increased, while the surface distance decreased after surgery, leading to the assumption that the surgery contributed to a re-establishment of both size and shape. The purpose of the study was to evaluate a semi-automatic segmentation tool to measure volume and perform shape analysis, before and after surgical reconstruction of orbital fractures. This study focused entirely on the radiological perspectives and no clinical data was presented. The semi-automatic segmentation method used in this study was shown to be fast and had a precision to detect volume differences down to 1.0 ml. The correlation between increased volume in the orbit and the development of enophthalmos has been frequently debated in the literature, with studies showing deviating results on the topic. Whitehouse et al and Yab et al presented that a certain amount of increased volume could predict the degree of enophthalmos. More recent studies from Schönegg et al and Alinasab et al do not confirm those results and suggest that increased volume is an unreliable prediction method for late complications. Schönegg et al could, however, identify a statistical correlation between fractures of the anterior and medial thirds of orbital floor and diplopia. They suggested that the location of the fracture might be of higher importance than the actual volume difference.

Hence, while the extent of enlargement of the fractured orbit cannot be used as a sole indication for surgery, it can be part of the entire assessment, together with clinical findings and patient symptoms. Accurate volume measurement and especially shape analysis in the preoperative and postoperative phase can be powerful supplements in diagnostics and evaluation of the surgical outcome. The shape analysis makes it possible to create a colour map and to visualise the local deviations between the fractured orbit in comparison to the intact side.

The semi-automatic segmentation method used in this study has some limitations. There is no reliable standardized way of identifying the anterior opening of the orbit. In this study, we created a planar boundary after placing four landmarks on the orbital rim. The definition of the anterior boundary is made manually, increasing the risk for inter- and intra-observer variations. The anterior part of the orbit has the widest diameter, so even a small deviation in the placement of the anterior boundary will have a large impact on the total volume measured. Another potential problem with the definition of the anterior opening is the imperfection that stems from different head positioning during the CT-scanning procedure before and after the surgery. This is also why we believe that the shape analysis could be of a greater value than the volume measurement alone. The shape of the fractured orbit could potential-
ly differ substantially from the intact side, even tough the volumes of the orbits are similar, and vice versa.

Development of an automatic procedure for defining the anterior opening, as well as the creation of a more stringent protocol for the CT-scanning procedure, could make this semi-automatic segmentation tool even more accurate. The protocol should contain a reproducible positioning of the patient and require a minimum slice thickness of 1 mm to reduce the partial volume effect.

In conclusion, a new semi-automatic segmentation method, based on a deformable surface model, was used for volume and shape analysis of a series of patients with unilateral orbital fractures. The study showed that the method was fast and has a precision of detecting volume differences down to 1 ml. We believe that semi-automatic segmentation in combination with 3D shape analysis can be a powerful tool for preoperative planning and postoperative evaluation for orbital fractures and should be part of further research.

6.3 Paper IV

Results
HASP is a fast and user-friendly VSP system with high precision, but relatively low accuracy, which is made for the surgeon him/herself to perform all relevant steps of the planning. The study showed a mean planning time of 15 minutes, including segmentation, for complex mandible fracture cases. Table 4 shows the accuracy for virtual reductions on the plastic skull model using the intact mandible as a reference. Figure 25 shows the intra-observer variability, described in mean absolute distance (MAD), maximum (Hausdorff) distance and volume overlap (DICE). Figure 26 shows the inter-observer variability. Figure 27 shows the intra-operator precision for one of the analysed cases and is visualised by a colour-coded distance map.
Table 5. This table provides data on accuracy for the different users of the planning method, describing the mean absolute distance (MAD), maximum (Hausdorff) distance and the volume overlap (DICE) between the intact plastic skull and the repeated virtual reductions. The table also shows the accuracy between the glued skull and the virtual reductions.

<table>
<thead>
<tr>
<th>MAD</th>
<th>Max</th>
<th>Volume overlap (DICE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1T1-INTACT</td>
<td>1.88</td>
<td>8.57</td>
</tr>
<tr>
<td>U1T2-INTACT</td>
<td>1.73</td>
<td>6.87</td>
</tr>
<tr>
<td>U2T1-INTACT</td>
<td>1.76</td>
<td>6.94</td>
</tr>
<tr>
<td>U2T2-INTACT</td>
<td>1.09</td>
<td>4.85</td>
</tr>
<tr>
<td>U3T1-INTACT</td>
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<td>8.05</td>
</tr>
<tr>
<td>U3T2-INTACT</td>
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</tr>
<tr>
<td>Mean</td>
<td>1.65</td>
<td>7.12</td>
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<tr>
<td>Min/max</td>
<td>[1.09, 1.88]</td>
<td>[4.85, 8.57]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MAD</th>
<th>Max</th>
<th>Volume overlap (DICE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1T1-GLUED</td>
<td>1.05</td>
<td>4.54</td>
</tr>
<tr>
<td>U1T2-GLUED</td>
<td>0.93</td>
<td>4.37</td>
</tr>
<tr>
<td>U2T1-GLUED</td>
<td>1.03</td>
<td>4.15</td>
</tr>
<tr>
<td>U2T2-GLUED</td>
<td>0.8</td>
<td>3.41</td>
</tr>
<tr>
<td>U3T1-GLUED</td>
<td>0.82</td>
<td>3.62</td>
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<tr>
<td>U3T2-GLUED</td>
<td>0.94</td>
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<td>Mean</td>
<td>0.93</td>
<td>3.93</td>
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<tr>
<td>Min/max</td>
<td>[0.8, 1.05]</td>
<td>[3.41, 4.54]</td>
</tr>
</tbody>
</table>
Figure 25. Intra-observer variability. The measurements from the plastic skull model are marked with orange data points
Figure 26. Inter-observer variability. The measurements from the plastic skull model are marked with orange data points.

Figure 27. Intra-operator absolute distance presented with a colour coded distance map.
Discussion
VSP in the field of trauma needs to be fast and user-friendly. Current commercially available CMF planning systems are based on the collaboration with a computer engineer to perform all the steps under close guidance of the surgeon.\textsuperscript{33-35} There is of course advantages with this setup, mainly that an engineer with advanced technical knowledge can perform all the pre-processing steps. However, there are also some drawbacks. The most obvious one is the time needed for the collaboration, fabrication and shipping of the relevant guides or implants. In both trauma and in reconstruction due to malignant tumours, the time for planning is limited. In such cases, it is therefore often not possible to use the existing commercially available planning systems. Another disadvantage is that the available VSP systems are primarily relying on 2D graphical interfaces. This requires the user to visualise complex 3D anatomical structures from a 2D view.

Clinical studies using VSP for mandible fractures are rare.\textsuperscript{4, 6, 81, 96} This is most likely due to time limitations in trauma cases, where the goal in general is to perform the surgical intervention as soon as possible in order to lessen patient discomfort and avoid tissue edema and inflammation, which can make the surgery more technically difficult at a later stage. Biller et al\textsuperscript{97}, investigated the relationship between timing of surgery and postoperative complications and demonstrated no difference in infections and non/malunion, comparing treatment within or after three days. The study could, however, identify that complications because of technical errors increased in the group treated after 3 days. Ellis et al\textsuperscript{78}, recommend as a rule of thumb, that mandible fractures should be treated as early as possible, since the vast majority of mandibular fractures are compound fractures. Given the above, for VSP to be viable for use in trauma cases, it would need to be both fast, as well as user-friendly enough for a surgeon to use on their own. This has created an interest for having an in-house solution for VSP that meets these demands.

Li et al.\textsuperscript{81} presented a study comparing VSP with conventional surgery for complex mandibular fractures. The planning was carried out through a web-session, but the physical models were printed at the clinic, thereby reducing the time normally needed for manufacturing and shipping. The study reported a significant decrease in operative time for the VSP group, in addition to reduced bleeding. The study suggests that the pre-shaping of the reconstruction plate makes the surgery faster and more accurate, especially for the edentulous patient without a normal occlusion as guidance. Repetitive bending of the plate could also lead to a weakness in the plate and thereby increase the risk of fatigue break.
The present study describes the workflow for using an in-house VSP-system including haptic technology for the planning of complex mandibular fractures. This novel planning setup was shown to be time-efficient, user-friendly and with high precision and relatively low accuracy. A weakness in the study design was the use of an artificial plastic skull to evaluate the accuracy. A cadaver skull would likely have been more appropriate to use, in order to also pose the challenges involved with segmentation of different tissue types. Furthermore, it may have been more suitable to randomize the patient cases, so that the user would not perform the same case two times in a row. The instant repetition of a case could have resulted in bias for the second planning session, stemming from a potential learning curve and the memory of the previous session.

In addition, there is a need to develop the planning system further to increase both the accuracy and the precision. The accuracy and precision were shown to be less than 2 mm. It is important to interpret these results with caution, since a deviation of 2 mm may seem like a significant issue in the clinical situation, but does not necessarily have a large impact. Firstly, a minimal rotation at the fracture site will propagate into a large deviation at the peripheral anatomical structures, leading to a high mean absolute distance between two objects. In this case, the clinical impact at the fracture site remains low, something that is not reflected in the numbers. Secondly, when evaluating the reproducibility (intra/inter-observer variability) for the retrospective cases, it is not possible to know the original shape of the mandible. Hence, two virtual reductions can only be compared to each other but not to the original state. Moreover, a small move or rotation of a mandible in one virtual reduction compared to another can result in significant measured deviations, even though the two virtual reductions may have exactly the same shape. This is because the measurements were made by superimposing the cranium and then calculating the deviations between two virtual planned mandibles.

Limitations of the current HASP system include limited resolution in the number of contact points in the haptic simulation, and the use of a haptic device only supporting 3DOF force output (no torque output). Improving the performance of the haptic simulation could increase the haptic fidelity of the system, and thereby make it easier for users to tell when bone fragments fit together.

For most mandible fractures, the treatment strategy is relatively straightforward. Due to this, VSP should not be used as standard. However, when it comes to more complex fractures with multiple segments or an edentulous or atrophic mandible, re-establishment of the 3D shape can be challenging, and VSP can be of significant assistance. In those cases, there is a need for a
load-bearing osteosynthesis, which often entails a long reconstruction plate. Accurately fitting a long reconstruction plate can be very time consuming and is highly dependent on the surgeon’s level of experience. Accurate fracture reduction is vital to re-establish the native shape of the mandible and thereby the function. Insufficient reduction and fixation will increase the risk for post-operative complications including mal-union/non-union and malocclusion. ⁷⁶

The eventual goal of HASP is to provide the surgeon with the ability to apply the virtual surgical planning in a fast, intuitive way, but also to facilitate the different steps trough the surgery, including plate choice and preoperative modification of the plate. This would potentially simplify the reduction of the fracture and the placement of the plate. It may also lead to a faster, more accurate surgery with less post-operative complications. A well-designed prospective clinical study is the next step to assess these claims.

6.4 Paper V

Results
The result of the literature search is presented in figure 28. The search resulted in 4389 studies, where 1540 were duplicates. The title and abstract of the remaining 2849 articles were screened independently by two of the authors. The full article was reviewed for 124 studies, but only 27 articles were finally included in the systematic review. The remaining 97 articles did not fulfil the inclusion criteria.

Descriptive data from the included 27 studies are presented in table 5. The total amount of patients in the VSP group was 524, while 770 were in the control group. The majority of the articles reported on reconstruction of the mandible or maxilla, though there were also studies regarding orthognathic surgery, orbital reconstruction, midface distraction and mandible fractures. A meta-analysis was conducted regarding operative time for mandibular/maxillary reconstruction, showing a reduction in operative time in favour of the VSP group with a mean difference of -84.61 min (95%CI -106.77, -62.45, p<0.00001), Figure 29. A meta-analysis was also conducted for ischemia time and hospitalisation, suggesting a reduction in both ischemia time and hospitalisation in favour of VSP, see figure 30 and figure 31.
Figure 28. Flow diagram of the literature search

Table 6. The tables on page 62 and 63 show detailed data of the included studies. Abbreviations used in the tables:
- **ND**: Not Described.
- **FFF**: Free Fibula Flap.
- **TMJ**: Temporomandibular Joint.
- **SD**: Standard Deviation.
- **VSP**: Virtual Surgical Planning.
- **NE**: Not evaluated.
- **SJ**: Single Jaw.
- **DJ**: Double Jaw.
- **a**: Same patients in both groups.
- **b**: Interquartile range.
- **c**: Min – max.
- **d**: From anastomosis to end
- **e**: median
- **f**: time for fibula molding, plate adaptation and insetting.

All times are written in minutes.
<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>2015</td>
<td>Proposal</td>
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<tr>
<td>2016</td>
<td>Proposal</td>
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<td>2017</td>
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<tr>
<td>2022</td>
<td>Meeting</td>
<td>Meeting held</td>
</tr>
</tbody>
</table>

**Notes:**
- Meetings are held to discuss the project progress and revisions to the proposal.
Figure 29. Forest plot regarding operative time.
Figure 30. Forest plot regarding ischemia time.

Figure 31. Forest plot regarding hospitalisation time.
Discussion

This systematic review suggests that VSP can reduce the total operative time and ischemia time for reconstructive CMF surgery. The study also shows slightly shorter hospitalization duration after reconstructive CMF surgery in the VSP group. Reduced operative time and ischemia time are known prognostic factors, not only for the free-flap survival, but also for the overall morbidity. Reduced time spent in the operation theatre will also likely have positive economic implications that outweigh higher upfront costs for VSP. Chang et al. presented the largest study with a total number of 92 patients, having mandible reconstruction with osteocutaneous free flaps from fibula (n=89) or scapula (n=3). The study evaluated the operative accuracy and efficiency for a VSP group and a control group. The study reported a high precision and a low deviation between the preoperative virtual plan and the actual outcome. The authors suggested that the improved accuracy and plating of the fibula to the mandible could be performed with less modification, which translated into shorter ischemia time and shorter total operative time. Ayoub et al. presented a prospective, randomised trial comparing VSP with conventional surgery for mandible reconstruction using vascularised iliac crest bone grafts. The results showed a decreased ischemia time for the VSP group, as well as a reduction in the amount of bone that was harvested in the VSP group compared to the control. The authors also identified a significantly smaller alteration of the condyle position in the VSP group.

Steinhuber et al. and Wrzosek et al. reported on the difference in preoperative planning time for orthognathic surgery, comparing VSP and conventional planning. Both studies showed VSP to take significantly less time during pre operative planning. The most obvious time saving was seen in the laboratory work.

Two studies, Fan et al. and Zielinski et al., reported on orbital reconstruction, comparing VSP and conventional planning. Both studies showed a reduced operating time. Fan et al. also described that VSP increased the accuracy and safety of the surgery.

The results from this study must be interpreted with caution due to the relatively small amount of included studies and patients. A weakness of the study is that many of the included studies had a retrospective design and were not randomized. Lacking randomisation can lead to a bias in the result due to the risk of differences in the groups, such as co-morbidities, the severity of the defect, and the difficulty of the actual surgery. An assumption could be that the surgeons would have a higher tendency to choose VSP for a more complex case, which could have biased the results. There is a need for a larger, prospective and randomized study to examine these issues.
7. Conclusions

Paper I, II
A method for generating a 3D model of the facial skeleton and dentition, including virtual bite registration, was developed and evaluated. The model has the potential to eliminate plaster cast models and traditional laboratory work, and may facilitate 3D computer-assisted-planning in orthognathic surgery.

Paper III
A semi-automatic segmentation method for the orbit was evaluated, showing a precision for detecting volume differences down to 1.0 ml. The combination of this semi-automatic segmentation and 3D shape analysis provides a powerful tool for planning and evaluating reconstruction of orbital fractures.

Paper IV
This study presents an in-house haptic assisted planning tool with high usability that can be used for preoperative planning and evaluation of complex mandible fractures. The planning is time-efficient and showed high precision but relatively low accuracy.

Paper V
This systematic review and meta-analysis suggests that VSP shortens the operative time and ischemia time for reconstructive CMF surgery. VSP also seems to shorten the preoperative planning time for orthognathic surgery.
8. Summary and contribution

Recent advances in scientific and technological knowledge have led to a revolution in imaging techniques and virtual planning. VSP and CAS have likely only begun the larger transformation that we will see in CMF surgery in the future. As we move from the surgeon’s subjective assessment to a more structured setup for preoperative virtual planning and intraoperative implementation, we will see both improved accuracy and efficiency. In this thesis, we have developed and evaluated different crucial steps in virtual planning in CMF.

Contributions of this PhD are:

• A workflow for creating an accurate 3D model of the facial skeleton and dentition was presented. The workflow also included a method for virtual bite registration to position the mandible into CR. It has the potential to eliminate plaster casts and model surgery and may facilitate 3D computer-assisted planning for orthognathic surgery.

• Evaluation of a semi-automatic segmentation method in combination with 3D shape analysis, showing that it provides a powerful tool for preoperative planning and postoperative evaluation for orbital fractures. The system can provide accurate and precise segmentation of both intact and fractured orbits and is time efficient.

• An in-house VSP-system including haptics for complex mandible fractures was presented and evaluated. The planning setup was shown to be time-efficient, user-friendly and with high precision. The system has shown potential to be a valuable tool for treatment of complex mandible fractures.

• A systematic literature review found VSP to shorten the operation time and ischemia time for reconstructive CMF surgery. It also suggests that VSP shortens the preoperative planning time for orthognathic surgery.
9. Future work

An important part of future work would be prospective, clinical evaluations of the virtual surgical planning methods described in this thesis. The included studies in this thesis are mainly focusing on the technical aspects and the accuracy and precision in the methods used. It is still relatively expensive to perform and invest in new technology with VSP and CAS and it is therefore of great interest to validate the clinical relevance. Several papers have been published in the field of VSP for CMF surgery but there are few randomised, prospective studies available.

Another crucial part of future work involving the methods developed and used in this thesis is how the virtual surgical plan can be transferred into the operating theatre. There is a need for more tools for designing and manufacturing guides and plates in an in-house setting.

An interesting project, we are currently working on, is a clinical study investigating the accuracy and survival of cranio-maxillofacial implants for facial prosthesis planned with VSP. The aim of this study is to investigate the actual agreement between the virtual plan and the implant position, as well as to study the survival and clinical appearance of the craniofacial implants.

Det viktigaste steget i virtuell kirurgisk planering är att skapa en noggrann avbildning av den anatomiska struktur som man vill arbeta med. I dag finns det flera olika medicinska bildtagningssystem som kan generera detaljerade 3D bilder av skelettet och mjukvävnad, t.ex. CT, CBCT, MR, intraoral skanning, ultraljud etc. Trots alla dessa tekniker så finns det inte en separat bildtagningsteknik som kan generera en noggrann 3D modell av både ansiptsskelettet, tänder och mjukvävnad. Det finns således ett behov av att kombinera olika bildtekniker för att uppnå detta, något som är speciellt relevant för ortognatkirurgi där det är av yttersta vikt att ha en 3D modell med exakt avbildning av ansiptsskelettet, tänderna och käkarnas relation till varandra.

En annan svårighet inom virtuell planering är att separera, s.k. segmentera, specifika anatomiska strukturer från resten av bilden. Ögonhålan är en struktur som utgör en stor utmaning när det kommer till segmentering. Detta på grund av ögonhålans lokalisation men framför allt på grund av de extremt tunna benväggar som finns i botten på ögonhålan och i den mediala väggen. Detta medför att kontrasten mellan ben och mjukvävnad kan vara låg och att det är svårt att avgöra var gränsen mellan de olika vävnaderna går vid segmentering.

Den här avhandlingen är baserad på fem delarbeten; två studier diskuterar och utvärderar noggrannheten av att kombinera CT/CBCT med intraoral skanning. Ett tredje arbete fokuserar på segmentering av ögonhål, den fjärde studien utvärderar ett nytt virtuellt planeringsverktyg för komplexa mandibelfrakturer och det avslutande femte arbetet är en systematisk litteraturöversikt och metaanalys som undersöker eventuella tidsskillnader mellan kirurgi som är planerad virtuellt och traditionellt utförd planering utan virtuella hjälpmedel.

Den här avhandlingen har bidragit med följande:

- Utvärdering av ett semi-automatiskt segmenteringsverktyg för preoperativ planering och utvärdering av orbita frakturer. Systemet är tidseffektivt och har en hög noggrannhet och precision. Verktyget kan användas för både form och volymanalyser.
- Ett klinikbaserat virtuellt planeringssystem som inkluderar haptik har utvärderats för komplexa mandibel frakturer. Systemet var användarvänligt, tidseffektivt, med hög reproducierbarhet men relativt låg noggrannhet.
- En systematisk litteraturöversikt och metaanalys visade att virtuell kirurgisk planering för mandibel/maxilla rekonstruktioner med olika typer av transplantat gav en kortare operationstid och ischemitid. Den visade också att virtuell planering förkortade planeringstiden för ortognatKirurgi.
11. Related work


Osseointegrated craniofacial implants have been in use since the 1970s and have significantly improved the potential for rehabilitating patients with larger soft and hard tissue defects. The prostheses have gained a stronger acceptance among patients due to better retention provided by the implants and improvements in the quality of aesthetic work done. In comparison to plastic surgical reconstruction, implant placement is a relatively simple and straightforward treatment, offering the patients a substantially improved quality of life. The use of implant therapy in this patient group requires consideration of potential benefits to be gained from the therapy. To better understand these benefits, this systematic review was conducted. The paper reports that craniofacial implants placed in the auricular region had a lower probability of failure than implants in the nasal or orbital region. Radiotherapy significantly increased the risk of implant failure. Soft tissue reactions were the most common complication after treatment with craniofacial implants.

Rapid and Precise Orbit Segmentation through Interactive 3D Painting
Nysjö J, Nilsson J, Malmberg F, Thor A, Nyström I. (manuscript)

In this paper, we present an efficient interactive tool for segmenting and measuring the volume of the bony orbit in CT images. The tool implements a 3D painting interface that allows the user to quickly segment or “paint” the orbital fat and soft tissue by sweeping a volumetric brush over the image. The brush modifies and updates the segmentation result in real time and takes distance and gradient information into account to fill out and find the exact boundaries of the orbit. A smooth and consistent delineation of the anterior opening is obtained by fitting a thin-plate spline to user-selected landmarks on the orbital rim. We evaluated the tool on ten CT images of intact and fractured orbits and showed a high intra- and inter-operator precision. The tool can produce segmentation results that are similar to manually corrected reference segmentations, but require only a few minutes of interaction time.
12. Acknowledgements

It is impossible for me to list all the people that have played part on my journey to completing this PhD. I would like to express my special appreciation to the following extraordinarily helpful and inspiring people who contributed directly or indirectly to this thesis, and who have provided encouragement and support along the way:

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Fredrik Nysjö, co-author and the other of the ultra-talented twins at Centre of image analysis, Uppsala University. Thanks for all the help and support in the VSP for complex mandible project.

Ingela Nyström, co-author, for valuable development ideas and always giving positive support.

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Folktandvården Västertorg, my first work place as a new dentist. I’m very grateful for this time and all the great people working there.

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13. References


79. AO Surgery Reference.
A doctoral dissertation from the Faculty of Medicine, Uppsala University, is usually a summary of a number of papers. A few copies of the complete dissertation are kept at major Swedish research libraries, while the summary alone is distributed internationally through the series Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Medicine. (Prior to January, 2005, the series was published under the title “Comprehensive Summaries of Uppsala Dissertations from the Faculty of Medicine”.)