The Virtual Craniofacial Patient – A Platform for the Future of Craniofacial Healthcare

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INTRODUCTION

Advances in Information Technology have greatly improved our standard of living, allowing us to experience the world, communicate, entertain and live in ways that we could not have imagined. Progression has come so predictably and expectedly that the metronome beat of advancement seems to follow Moore’s Law\(^1\). In the last years several innovative and technological advancements have been made in craniofacial health sciences, with many of these now available or soon to be available. A related progression is the application of the data and information garnered from these technologies. Therefore, the Craniofacial Virtual Reality Laboratory was created at the University of Southern California to embark on the “Virtual Craniofacial Patient” (VCP) project. The overall goal of the VCP project is to create a digital platform for information technology related to craniofacial care (Figure 1). Various forms of biologic craniofacial data are acquired and assessed in the visualization domain. Detailed knowledge of craniofacial form and function provide the basis for the next two domains of simulation and virtual reality. Processing and integration of this data are managed in the domain of simulation for such purposes as treatment planning/simulation and decision-making. The domain of virtual reality includes digital model construction and human-computer interfaces for interactive viewing and virtual experiences. These domains broadly cover many subjects and are inter-related. The products and benefits of the VCP project will be in patient care, education and research.

VISUALIZATION

Comprehensive and precise knowledge of the biologic state is invaluable to all disciplines devoted to the craniofacial complex. Ideally, visualization provides accurate patient specific anatomic (hard and soft tissue) and functional information (motion, occlusal forces, speech, swallowing) using multi-modal approaches. These approaches provide for revolutionary applications in patient analysis, diagnosis, treatment planning and therapeutics. Furthermore, as technologies available for diagnosis and therapeutics are becoming more advanced and sophisticated, such as the development of minimally invasive surgical techniques and computer-assisted therapy, the availability of accurate 3-dimensional information is critical for successful outcomes. In this report, we primarily discuss recent developments in 3-dimensional visualization of the face, craniofacial skeleton, the dentition, and mandibular function.

3-Dimensional Facial Image Acquisition

In current practice, photography is the standard for facial imaging. Clinicians primarily use angular and relative information from photographs but rarely utilize metric information due to lack of standardized views, magnification and perspective. Conceptually, visualization of the craniofacial complex in 3-dimensions, would include the soft tissues of the face as facial appearance and esthetics is of paramount patient concern (Marsh and Vannier, 1993). Indeed, many clinicians plan treatment from the outside in, that is, treatment goals are established for optimal facial esthetics and the requisite osseous and dental movements are then determined with these goals in mind. However, imaging and simulation of the facial soft tissues are formidable and complex research and clinical challenges that lie ahead.

Imaging of the face can be accomplished using many available light or laser-based camera systems. By enlarge, all of these systems require significant post-processing of the acquired data to “stitch” together multiple views of the face, blend, texture, and smooth the surfaces. Aside from the time-consumption and technical demands of these tasks, post-processing of the data can significantly alter the dimensions and appearance, particularly over smoothing. While there have been reports on the use of 3-dimensional facial images in evaluation of facial soft tissue changes following orthognathic surgery (Techalertpaisarn and Kuroda, 1998), these approaches and systems have not been critically validated. The task of

\(^{1}\) The observation made in 1965 by Gordon Moore, co-founder of Intel Corporation, that the number of transistors per square inch on integrated circuits had doubled every year since the integrated circuit was invented. Moore predicted that this trend would continue for the foreseeable future. In subsequent years, the pace slowed down a bit, but data density has doubled approximately every 18 months, and this is the current definition of Moore's Law, which Moore himself has blessed. Most experts, including Moore himself, expect Moore's Law to hold for at least another two decades.
validation of these systems for facial imaging is difficult due to the multitude of variables in post-
processing and the conditions of image acquisition in the clinic.

Clinical challenges in utilization of these systems add further complexity to this topic (Ayoub et al., 1996). All systems suffer from potential for patient movement and alterations of facial expression between the multiple views needed to construct a 3-D model of the face. Laser-based systems are at risk for patient movement during imaging and the use of lasers remains a safety concern. While these systems are deemed safe for use with adults, the FDA has no statement on their safety in children, which represent a majority of the orthodontic and craniofacial treatment group. The light-based imaging systems generally lack the precision of the laser-based systems and suffer from image artifacts due to skin tone, color and reflectance. Additionally, the majority of 3-D imaging systems utilize frontal and three-quarter facial views to produce a facial model, however this approach does not provide sufficiently accurate representations of the facial profile. The “profile” view generated from these systems is not a true view of the facial profile as one would have with a camera positioned from the patient’s profile. The generated “profile” can be distorted by several millimeters and lack detail of specific features, especially in the lower face and lips (Figure 2). This deficiency is a significant setback as much of our knowledge of growth and development and treatment outcomes is based upon the profile view! A related but more overwhelming drawback is the absence of a 3-dimensional facial image database for reference purposes (Altobelli et al., 1993). Normative 3-D craniofacial databases that are age-, gender-, race-specific are greatly needed to permit advancements in the use of 3-D facial imaging in diagnosis and treatment planning.

It is clear that several significant research problems must be solved in order to make use of 3-D facial images in computer models of craniofacial treatment simulation. Several major technical and methodological developments are needed. These developments encompass large areas of research, some of which are currently in progress and are formidable challenges in themselves.

3-Dimensional Craniofacial Skeletal Imaging
Clinical demand for 3-dimensional skeletal information has always existed, particularly for assessment of transverse problems and asymmetries, and in recent years, the demand has increased with the introduction and utilization of newer clinical procedures such as placement of dental implants, distraction osteogenesis and adjunctive cosmetic surgery.

Early attempts at 3-dimensional craniofacial skeletal imaging include the Bolton cephalometer that utilized two x-ray heads placed 90 degrees to one another, imaging simultaneously to capture a lateral and a postero-anterior cephalogram of the patient. The paired images were then used to mentally reconstruct a 3-dimensional perspective of the craniofacial skeleton. This approach was used for limited research activities and was never adopted for widespread use by clinicians.

A limitation of the above system was the difficulty in 3-dimensional reconstruction, a problem that can be resolved with photogrammetry approaches to anatomic reconstruction (www.acuscape.com). This approach takes into account the spatial relationships between the x-ray source and sensor(s). Recently a method has been developed to use close-range photogrammetry algorithms to determine the precise location of the source, sensor and anatomy by measuring geometric effects of the projection geometry on a calibration frame placed into the field of view and rigidly attached to the patient during imaging sessions (Figure 3). The measurements can be used to construct models and spatially stitch together various image sets. The advantages of this system include the ability to calibrate the standard 2 dimensional images currently used in orthodontics (lateral and PA cephalograms) without the addition of capital equipment and combine them to produce a digital model (Figure 4).

Computed tomography (CT) scanners developed for imaging the entire human body have also been used for head and neck imaging to provide valuable 3-D information. However, significant disadvantages of this approach are: poor image quality, particularly in the dental region; high radiation exposure to a sensitive anatomic region; and high equipment costs as well as patient charges, thereby limiting access, availability and utilization. Recently, novel enhancements of CT technology have brought forward devices optimized for dental imaging with a fraction of the radiation dose of traditional CT (Mah and Bumann, 2001).
general, these devices feature a cone-beam projection of x-rays which produces much less radiation scatter compared to the conventional fan-shape projection, a reduced chamber volume, and real-time feedback between the digital sensor and x-ray source. This feature allows for increases or reductions in x-ray energy to account for variations in patient size and tissue density as the patient is being imaged to provide optimal images while further reducing radiation exposure. The precision of these systems is in the range of 0.10 to 0.28 mm which is approximately a five to ten-fold improvement upon conventional CT. Speed of image acquisition is also greatly improved with imaging times of approximately 60 to 90 seconds.

A large advantage of 3-D volumetric imaging over traditional films is the ability to "slice" through and view the volume from any chosen perspective (Figure 5). These "slices" can also be made to produce viewpoints corresponding to traditional planar films such as the panoramic view (Figure 6). Furthermore, the operator can select to view specific opacity values to highlight structures of interest (Figure 7). A fully opaque view shows only the surface while semi-opaque views reveal structures beneath.

3-Dimensional Dental Imaging
Dental images from radiographic reconstruction techniques and CT approaches lack sufficient accuracy for practical use. Over the last few years, several approaches have been developed to obtain high-resolution 3-dimensional images of the dentition, which can generally be classified as: destructive and non-destructive scanning. Direct and indirect methods exist within the latter category. Destructive scanning approaches involve removal of a thin layer of the impression and/or stone by sanding (www.aligntechnologies.com) or slicing (www.orthocad.com). Sectional images are acquired between removal of layers to produce a stack of images that are used to reconstruct the 3-D model of the dentition. One technique of non-destructive 3-D dental imaging involves use of a laser to scan a stone model from several perspectives (Figure 8) and stitch the overlapping views together to produce a dental model (emodels™ from www.geodigmcorp.com). Direct dental imaging is also possible using a recently developed, light-based 3D-intraoral scanner (Figure 9) (OraScanner™ from www.OraMetrix.com). A defined pattern is projected onto the dental crowns and its distortion is recorded by a small video camera. The stamp-sized images are streamed to a computer, processed and stitched together to create a complete dental arch. A dental arch can be imaged in approximately one minute.

3-Dimensional Jaw Motion Capture
Movement of the mandible is very complex and not easily recorded. Its movement has historically been simplified to rotation about a single hinge axis. However, the concept of mandibular hinge axis is controversial from a practical and a conceptual basis as there is no universal agreement on methods of locating the hinge axis and its existence has been brought into question. Recent studies have found that the mandibular opening and closing cannot be derived from pure rotation movements performed around the intercondylar axis, not even in the first millimeters of motion (Ferrario et al., 1996). Translation and rotation are always combined, and the position of the center of curvature changes during the motion, showing different characteristics in the open and close movements (Ferrario et al., 1996). Comparisons of tracings of hinge-axis point and the kinematic-axis point in asymptomatic volunteers show that during opening and closing, the trajectory of a single condylar point cannot reliably represent condylar motion (Morneburg and Proschel, 1998). However, in current practice, the center of the condyle is one of the reference points registered by a face-bow in preparation for surgery. This point is later used to simulate autorotation of the mandible following repositioning movements of the mandible and/or the maxilla. This approach can lead to severe mal-positioning of the jaws, particularly in surgery involving two jaws simply because the simulated axis of rotation is not related to the true path of mandibular motion (Nattestad et al., 1991; Nattestad et al., 1992). This evidence supports previous observations describing significant differences between the planned and immediate postoperative position of the maxilla after Le Fort I osteotomy (Pospisil, 1987; Kahnberg et al., 1990). Therefore, it is clear that accurate 3-dimensional knowledge of mandibular movement is necessary for diagnosis and treatment planning/simulation.

Recently light and ultrasonic-based systems have been developed to record mandibular position and movement. These systems allow for recording of mandibular movements in real time, recording and display of the 3-dimensional movements in digital form. Opticoelectric systems using CCD cameras to
track light-emitting diodes on a headframe and facebow (Miyawaki et al., 2001) have been developed (Tokiwa et al., 1996). The mean measurement error of this system is 150±10 µm (Tokiwa et al., 1996). However, this approach is time-consuming, requires attachment of bulky hardware on the patient and involves a complex arrangement of cameras. Since, a newer approach utilizing ultrasonic sensors attached to a headframe and emitters firmly attached to the mandibular dentition has been developed (Zebris GmbH) (Figure 10). The advantages of this system is the ease-of-use, significantly less hardware and an accuracy of ~100 µm with a data measurement rate of 100 measurements/second. The parameters of functional analysis, in addition to the settings of a fully adjustable articulator [hinge axis (HA), condylar inclination (CI) and immediate-side-shifts (ISS)] can be calculated and issued in a report.

SIMULATION

Accurate visualization technologies provide the accurate data from which a digital model of the patient/ the "Virtual Craniofacial Patient" can be constructed for SIMULATION activities that include treatment planning, decision-making, illustration, research, education and others. Within this domain are several areas in current development such as: (1) image integration and model construction, (2) model analysis and manipulation, and (3) animation and function. Within the first area of development are: the integration of the various forms of data such as the dental models with the skeletal CT data (Figure 11). Concurrently, imaging data can be segmented to isolate anatomic structures such as the mandible for finite element analysis (Figure 12) and animation.

An accurate “Virtual Craniofacial Patient” model will allow the operator to simulate and test various treatment alternatives, developmental and disease hypotheses, different restorative materials and predict risks and outcomes such as esthetics or function with much more precision. Secondly, researchers in biomedical engineering and biomimetics may use these models to design and test materials and approaches, reducing the need for clinical trials. Thirdly, the computer model allows for realistic animation and reproduction of function. Video sequences of facial expression and motions produced by the same person will be analyzed to extract information regarding specific facial movements, deformations, and appearance changes. This information may then be used to control a 3D animated model that mimics the appearance and behavior of the real person. Through future evolutions of these methods approaches will be developed to simulate speech, mastication and swallowing. These advancements will have applications not only in healthcare, but manufacturing of devices, communication, entertainment, and many other aspects of our society. These ambitions will be future developments and at this time, small steps have been taken simply in the simulation and manipulation of soft tissue and bone.

Soft Tissue Simulation

Assuming that the imaging hurdles of 3-D facial imaging are overcome, the next significant problem is the computer simulation of soft tissue response in response to mechanical forces and therapy. Since the soft tissues of the face are composed of skin, muscle, connective tissue, fat, nerves, vessels and other tissue types, realistic soft tissue simulation is a very complex task. Animation of the facial muscles in itself is a significant challenge. Researchers have developed simple models of the muscles of facial expression from CT data (Aoki and Hashimoto, 1998). Recently, the muscles of mastication and their effect on mandibular motion were modeled (Koolstra et al., 2001). Various models of facial soft-tissue simulation have been described that include mass-spring (Koch et al, 1996), finite element (Motoyoshi et al, 1993; Koch et al, 1996), and long element (Balaniuk, 2002), approaches. These models are still in development and clearly there is room for improvement as comparisons of pre- and post-surgical results in a sample of craniofacial surgical patients revealed large discrepancies between the predicted and actual outcomes (Koch et al, 1999). Other approaches that account for tissue viscoelasticity and relaxation have been developed to obtain more accurate results (Keeve et al, 1998). More recently, researchers have proposed a combination of methods to simulate changes in different regions of the face. A surface normal-based approach was used to model the chin while a ray projection-based method was used to model the remainder of the face (Xia and Samman et al., 2000). However, no quantitative comparisons between predicted and post-operative outcomes have been made using this approach. Despite these recent developments, further advancements are necessary to realistically simulate soft tissue responses to surgery.
Digital Manipulation Of Bone
Computer tools have been developed to simulate bone surgery with the objective of realistic simulation, however this research topic is relatively new with significant progress ahead to achieve this goal. Additionally, bone surgery is more difficult to simulate in bones with complex shapes, such as those of the craniofacial complex. Computer methods have been developed to bend, move, and remove bone using osteotomy tools on a wireframe model (Sloten et al., 1996; Xia and Ip et al., 2000). Deformable models of the skull have been developed to simulate craniofacial surgery (Delingette et al, 1994). Following simulation of osteotomy, a virtual 3-D hand is used to shape an elastic model of the skull. However, research has not confirmed if these digital actions, particularly bending and elasticity of bone, are realistic. In addition to osteotomy functions, 3-D motion of the bone segments must be tracked and quantified (Everett et al., 2000).

VIRTUAL REALITY
The products of VISUALIZATION and SIMULATION may be brought together for development of VIRTUAL REALITY (VR) applications. VR is made possible with a graphic interface, such as a head-mounted display (HMD), that allows the user to view 3-dimensional objects and environments and a navigation system, such as hand tracking devices, motion-coupled HMDs, or motion-tracking body suits. The haptic (touch, or having to do with touch) and kinesthetic (sensing orientation and position in space) components of the environment complete the interactive experience.

The successful track record of flight simulators in the training and continuing education of pilots has inspired the application of this technology to medical and dental training. The highly visual and interactive nature of VR has proven to be useful in understanding complex 3D structures and for training in visuospatial tasks. In healthcare, applications of VR have been developed for training in: arthroscopy, knee surgery, endonasal sinus surgery and soft tissue surgery. Initial validation studies on simulators have shown differences between experienced and novice surgeons, that training improves over time, and that simulator task performance is well correlated to actual task performance. Another educational program is cadaver dissection that is the "gold standard" for anatomic and surgical training, but has serious limitations. The most significant threat to use of cadavers for teaching is the availability of cadavers has declined over the years, leaving a shortage for teaching programs. Related to this, access is often limited, reducing opportunities to practice, experiment and refine techniques. Additionally, specific training situations are difficult to simulate. These situations have moved training programs towards the adoption of virtual reality and computer models for training.

Augmented reality is a hybrid of virtual and real environment spaces, which are co-registered and simultaneously visualized. Its application is in surgical navigation where the surgeon is provided with visual access to invisible data of anatomy, physiology, and function using a head-mounted display. Early results indicate that the surgeon’s perception is enhanced, leading to unencumbered surgery and improved results.

PATIENT CARE

Predictive Medicine
The current paradigm for patient treatment relies heavily on 2-dimensional diagnostic imaging data to define the present state of the patient, empirical data to evaluate the efficacy of prior treatments for similar patients, and the judgment of the clinician to decide on a preferred treatment (Mah, 2002). The individual variability and inherent complexity of human biological systems is such that 2-dimensional imaging and empirical data alone are insufficient to predict the outcome of a given treatment for an individual patient. Predictive medicine involves: accurate data and patient information for improved diagnosis; computer-assisted treatment planning, simulation and therapeutics. In this paradigm, the clinician utilizes a realistic and accurate 3D model of the patient and computational tools to construct and evaluate a combined anatomic/physiologic model to simulate the outcome of alternative treatment plans for an individual patient. For example, a surgeon can simulate different paths of access to difficult surgeries and predict the response of related tissues and structures to the surgical procedure and
healing. Early reports show clear benefits of predictive medicine in reducing complications of surgery such as the reduction of operating time, blood loss and overall morbidity.

Another aspect of the predictive medicine paradigm is to involve patients in the planning process. Clear benefits of computer imaging and simulation have been shown in the area of patient communication. These technologies have been shown to help patients understand their problems and to help provide a clear and realistic pretreatment informed consent.

Telemedicine
A realistic and accurate computer model of the patient (the “Virtual Craniofacial Patient”) enables multiple distribution and viewing and allows for potential applications in therapy and outreach programs. Digital images of the patient contain many benefits, some of which include: access to expert consultation, improved monitoring and communication, education, and data collection for research. Additionally the “Virtual Craniofacial Patient” will contain sufficient dimensional accuracy to produce therapeutic aids such as splints, surgical templates, and other devices by CAD/CAM technologies. This will permit the clinician to not only diagnose and treatment plan remotely but also provide select therapies. Surgery and other clinical procedures may be performed remotely. These abilities will truly enhance our efforts at community outreach, regionally, nationally, and internationally. Simply put, many more patients in need will have access to the best healthcare possible.

EDUCATION
The ideal learning opportunities afforded by simulated and virtual reality environments have prompted their development as learning modalities for medical and dental education and training. Recently, educational tools such as a virtual tooth atlas (Herbranson, 2002) and interactive simulation of tooth brushing (Gockel, 2002) have been reported for dentistry. Simulators have been used extensively in the military and industry because they offer testing environments that are controllable, secure, safe, and feature improved cost-effectiveness. These benefits have sparked interest in the development of simulators for healthcare education and training for potentially dangerous situations (ie, new or complex medical procedures).

Traditional surgical training has been based on the preceptor or apprenticeship method, wherein the resident learns with small groups of peers or superiors in the course of patient care. Teaching methods in this type of “on-the-job training” have evolved over time and include more or less formal educational practices, such as bedside teaching rounds, case conferences, seminars, and grand rounds. The operating room is often termed “the surgeon’s classroom” as it is the venue to demonstrate and learn technique and in many instances is the resident’s first attempt to practice surgical skills.

Numerous factors are exerting tremendous pressure on the traditional residency training structure. The funding of graduate medical education is threatened while the per capita workload increases, due to limits on the number of postgraduate training positions available. Meanwhile patient demand for services has risen at a constant rate and surgical techniques are becoming more sophisticated and demanding forcing residents to learn and work faster while opportunities for error are increasing. Additionally, residents may not have the opportunity to treat certain types of patients necessary to their education due to the rarity of these types of patients or events, nature of their program or other factors such as the geographic location of their training. Given these forces, several leaders have suggested that the next rational step in surgical education and training is the adoption of computer-based simulators. Following this lead, we envision courses to be designed and introduced for students interested in learning about computer-assisted treatment.

Although in its infancy in healthcare, simulation has been used successfully in a variety of settings. Simulators have been used to teach paramedical personnel triage and assessment skills, and to create various scenarios for the teaching and assessment of skills in advanced trauma life support and advanced cardiac life support courses. In anesthesia, simulators expose clinicians to crisis situations that they would not otherwise routinely experience. Anesthesiologists trained on these simulators responded more quickly and appropriately when handling these crises.
RESEARCH

Three-dimensional simulation and analysis of patient parameters, materials, treatment techniques, and other variables is a very powerful research method leading to better decisions and outcomes. For example researchers have modeled different techniques of skin resection and designed an approach that would avoid unsightly scars formations. Any number of variables could be tested and evaluated before approaching the patient. Computer simulation may reduce some types of clinical trials and accelerate development of new methods. Centralized data repositories may be designed to facilitate collection of data in multi-center clinical studies for outcomes determinations.

With accurate biologic data garnered from patient care and the basic sciences, the science of theoretic biologic modeling could be used to evaluate developmental and disease theories. Additionally theoretic modeling may be used to simulate future craniofacial growth and integrated into treatment simulations and planning.

Summary
The "Virtual Craniofacial Patient" is a digital platform for the future of craniofacial healthcare based upon Visualization, Simulation, and Virtual Reality technologies to benefit patient care, education and research.
REFERENCES


Figure 1. Schematic of the Virtual Craniofacial Patient Project
Figure 2. Facial Profile from a 3-D Facial Imaging System vs. Camera Profile.
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(Image courtesy of Acuscape International)

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(Image courtesy of Dr. Ivan Dus)

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