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Review

Three dimensional (3D) modelling and surgical planning in trauma and orthopaedics

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ABSTRACT

Introduction: Three dimensional (3D) modelling facilitates visualization, manipulation, and analysis of image data, the three dimensional format of such image, allows a better appreciation of the geometry, size, and exact relationship between diseased and normal tissue. The role in orthopaedic surgical planning is highlighted.

Discussion: Surgical procedures in **orthopaedics** and trauma rely on imaging, which in addition to making the diagnosis also assist in planning the elected surgical procedure through to a successful execution.

In the area of trauma management, the **use** of 3D modelling eases the execution of fracture operative approach, reduction and appropriate fixation, especially in complex fractures, like in the acetabulum. Post trauma correction of deformities is made easier using 3D modelling in the preoperative surgical planning.

For the purposes of tumour excision, a more acceptable margin of excision can be planned and successfully implemented.

There is an increasing role for computer assisted procedures in arthroplasty, the use of a 3D image for preoperative planning promises to deliver patient specific bone cut in dimensions that will allow less of inappropriate loading thereby promoting longevity of the implant especially in younger patients.

Conclusion: The processes for acquiring **3D** images need to be made simpler and easier to gain more widespread use in orthopaedics and trauma.

Introduction

The processes that are applied in the acquisition of multidimensional image data to facilitate visualization, manipulation, and analysis of the information captured in the image data are described as three dimensional modelling (3D). The sources of digital multidimensional images are, computerized tomography (CT), magnetic resonance imaging (MRI), positron emission tomography (PET), single photon emission computed tomography (SPECT), ultrasound (US), functional

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MRI (fMRI), magnetic source imaging, and surface light scanning.[1]

Three dimensional modelling operations can be divided into four steps: i) pre-processing, which is about defining the object system, ii) visualization, which permits viewing and comprehending the structure and dynamics of the object system, iii) manipulation, which is an operation for virtually altering the individual objects or the relationships among the objects in the object system as in a virtual surgical operation, and lastly, iv) analysis, which is used to quantify the morphological and/or functional information about the object system.

The most imaging modality used in orthopaedics and trauma is the plain X-ray in which a beam of X-ray is produced by an X-ray generator and is projected towards the body region to be visualized. According to the density and composition of the different areas of the region, a proportion of the X-rays are absorbed by various tissues in the body. The X-rays that pass through are captured behind the body part with a detector (film sensitive to X-ray or a digital detector) which provides a two-dimensional (2D) representation of all of the structures superimposed on each other. Other imaging modalities that are routinely used are, computed tomography (CT) scanning, ultrasound, and magnetic resonant imaging. Computed tomography scanning, utilizes X-ray beams passed into the body and produces a set of data that can be manipulated through a process known as "windowing", to demonstrate various bodily structures based on their ability to block the X-ray beam. Historically, images were generated in the axial or transverse plane perpendicular to the long axis of the body; modern scanners allow this volume to be reformatted in various planes or even as a volumetric 3D representation of structures.

Ultrasound uses a probe containing multiple acoustic transducers which send pulses of sound into the body. Tissues of varying density (acoustic impedance), reflect back to the probe some part of the sound which is detected as an echo. The time taken for the echo to travel back to the probe is used to calculate the depth of the tissue interface causing the echo. The difference between the acoustic impedances, determine the size of the echo, if the pulse hits gases or solids, the density difference is so great that the majority of the acoustic energy is reflected, reducing the perception of deeper structures. The frequencies for medical imaging are generally in the range of 1–18 MHz. The velocity, frequency or wavelength of a wave can be calculated by using the formula $v = f\lambda$ if the other two values are known, where (v) is the speed of the wave which is measured in m s^{-1}, frequency (f) is the number of times a particle oscillates per second and is measured in Hz, and the wavelength (λ) is the distance between two compressions or rarefactions and is measured in m. Ultrasound uses high frequency sounds that are higher than the human ear can perceive, higher frequencies of ultrasound produce better resolution however they have short wavelength, are absorbed easily and are not as penetrating. Therefore high frequency ultrasound is used for scanning areas of the body close to the surface and low frequency ultrasound is used for areas that are deeper in the body.

Magnetic resonance imaging (MRI) utilises a powerful magnetic field to align the magnetization of some atomic nuclei in the body, and radiofrequency fields systemically alter the alignment of this magnetization; tissues appear differently as a result of the amount of protons they are able to generate. MRI provides good contrast between the different soft tissues of the body, which makes it especially useful in imaging the brain, muscles, the heart, and cancers compared with other imaging techniques such as computed tomography (CT) or X-ray. Unlike CT scans or traditional X-rays, magnetic resonance imaging does not use ionising radiation.

Surgical procedures tend to have better outcomes if they are preceded by the appropriate planning. It is imperative to visualize the lesion to be treated directly or indirectly to offer appropriate treatment. Surgical procedures in orthopedics and trauma rely on imaging, which in addition to making a diagnosis, helps in planning the elected surgical procedure through to a successful execution.

This review highlights the role of three-dimensional imaging in the pre-operative assessment and planning of surgical interventions in orthopaedics and trauma.

Three dimensional imaging methods that are appropriate for surgical planning in trauma and orthopaedics include computed tomography (CT) scanning especially, for the study of the geometry in articular fractures, this method is also useful in defining the fracture geometry in complex bony anatomy, for example the acetabulum and the calcaneum when surgical treatment is indicated. Magnetic resonance imaging (MRI) scanning has been useful in characterising, determining the boundaries and staging of bone tumours and soft tissue sarcomas. Ultrasound scanning (USS) has been used to determine the nature of lumps and bumps and in determining extent of fluid collection in tissues, tissue plains and the presence and estimation of fluid in deep seated joints such as the hip.

Images can be obtained in two and three dimensions with computed tomography scanning (CT), magnetic resonance imaging (MRI) and ultrasound scanning (USS).

Orthopaedic trauma surgical procedures generally involve close or open reduction and internal fixation of fractures, in which metallic implants are used to stabilize the fractures in the best reduced position achievable, in certain circumstances such as in intra-articular fractures, precise reduction must be attained and rigidly stabilised to limit or prevent the later complication of degenerative disease of the involved joint. In elective orthopaedic surgery, procedures commonly performed include joint replacement (partial or total), the correction of deformities (congenital or acquired), ligament reconstruction e.g., the anterior cruciate ligament (ACL) and the excision of benign or malignant tumours. The surgical treatment of benign tumours are usually limited to simple excision, which is primarily marginal but occasionally includes wide excision, but the treatment of malignant tumours of the bone or soft tissue sarcoma may necessitate wide excision to prevent recurrence with preservation of the limb.

Treatment of fractures

In the area of trauma management, the use of 3D modelling in preoperative surgical planning has been shown to make the procedure easier with satisfactory outcomes especially in complex fractures, such as those in the acetabulum.

Although the functional anatomy of the pelvis and acetabulum is well studied[2–5] and 3D CT has improved imaging, a complete understanding of the fracture lines remains difficult. Another problem is the choice of the correct operative approach, which is especially important in acetabular surgery. The reduction of bone fragments, which is usually very demanding, represents a key element for the normal post-operative biomechanical functions of the pelvis and the hip joint. A preoperative 3D model that allows the fracture fragments to be reduced as well as possible (Fig. 1), and the appropriate implants to be selected and applied prior to actual procedure will make the procedure easier and the choice of surgical approach to the fracture site can be carefully planned. An example is the use of SQ pelvis software which is a 3D surgery planning and simulation tool, developed to simplify the evaluation of different possible operative approaches and possibilities. This tool enables complete virtual operations on the model acquired from real patient data. It therefore helps surgeons to better understand the situation prior to going into the operating theatre, and when compared with traditional diagnostic and planning procedures, the end result is greater accuracy and simplicity of surgical planning, which improve the surgeons' efficiency in the preoperative planning and in the actual surgical procedure.

Cimerman and Kristan in 2007[6] reported an international evaluation study of acetabular fracture surgery performed in 10 centers in Germany, Hungary, Israel, Poland, Croatia and Slovenia. Twenty-eight cases of acetabular fracture operations were planned using the SQ pelvis tool.

The surgeons evaluated the SQ software; completely clinically relevant (5/5) points in 14 cases, clinically relevant (4/5) points in 9 cases, and partially clinically relevant (3/5) points in 3 cases. The presented software enables a complete virtual operation on real patient CT data, including osteosynthesis and C-arm simulations.

Three-dimensional modelling has been used preoperatively to evaluate intraosseous space available for percutaneous screw fixation in fracture treatment[7] and has been used in the preoperative planning of treatment of other irregular bone fractures. The use of intraoperative 3D imaging has been proven to be beneficial in achieving better reduction and stabilization of fractures without adding significant time to the overall procedure.[8]

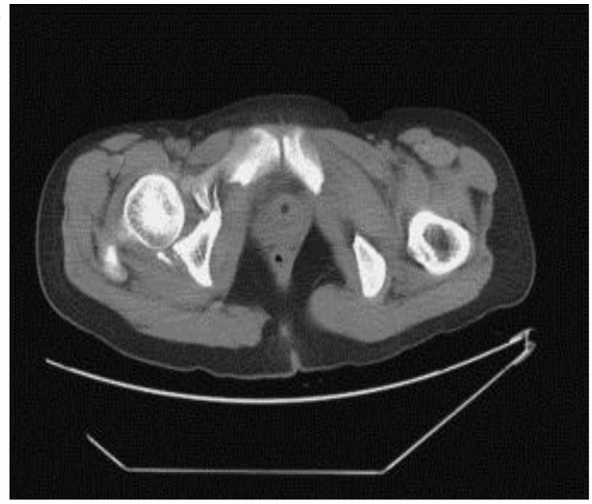
The use of 3D imaging in the planning and execution of open reduction and internal fixation of fractures in the distal radius and articular fractures of the knee involving the tibial plateau and the distal femur has become a common practice where the facilities are available.

It is envisaged that post trauma correction of deformities can be made easier using 3D modelling in the preoperative surgical planning, and a computer assisted versus non-computer assisted preoperative planning of corrective osteotomy for extra articular distal radius mal-union to be carried out as a randomized control trial has been proposed.[9]

Fractures in the long bones, especially the tibia and the femur are more commonly treated with intramedullary nailing. In closed injuries there is a special desire to mobilise adjacent joints early, thereby limiting joint stiffness and promoting earlier rehabilitation. An essential aspect of intramedullary nailing is approaching the precise entry point for the nail as recommended by the designers of the device. Selecting the most fitting nail design from an array of devices requires careful planning. Intramedullary nailing is the standard fixation method for displaced diaphyseal fractures of the tibia in adults.[10,11] The bends in the modern tibial nails allow for easier insertion, enhance the 'bone–nail construct stability, and reduce axial mal-alignments of the main fragments.[12–14] In addition to the applications in implant design, three-dimensional modelling has been used to conduct a quantitative fit assessment of different nail designs and could potentially be suitable for pre-operative planning by enabling the surgeon to choose the most appropriate nail design for the anatomy of a particular patient (Fig. 2); this will lead to less mal-alignment when treating tibial fractures with an intramedullary nail, which through an anatomical reduction, will facilitate a full recovery.[15]

Three-dimensional reconstructions have found successful applications in the evaluation of the spinal column. In the injured patient, the presence and extent of the fracture is important. Although the fractures can be diagnosed by plain X-rays, the true extent is best documented on a 2D or 3D display

(a)



(b)

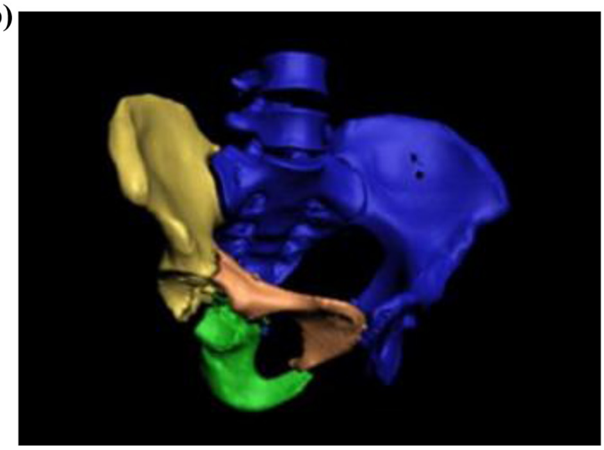


Fig. 1 – a Axial CT image of acetabular fracture. Injury. 2011 Oct; 42(10):1121–4, b Three dimensional reconstruction of the displaced T-shaped acetabular fracture. Reprinted from Ref. 21 with permission from Elsevier.

Fig. 2 – Left: tibia model with the lateral half of the cortex shell removed to reveal the 3D model of the inner cortex surface. Middle: semi-transparent model of the bone's inner cortex surface with positioned nail. The black oval marks the region where the nail protrudes from the medullary cavity. Right: sectioned cortex shell with positioned nail model. *Injury, Int. J. Care Injured* 2010; 41(2): 216–219.

and small bone fragments which may extend into the canal can be better visualized. Potential safe location of pedicle screws for stabilization can be determined preoperatively.

Arthroplasty

Joint replacement has shown good results at alleviating pain in severe osteoarthritis of the hips and the knees. This results in improved function in elderly patients, who are less active. There is increasing demand for joint replacement in younger patients for various indications especially post traumatic knee derangement which progresses to early osteoarthritis and compromises activities of daily living, but the survival of the implanted devices is known to have direct correlation with the level of activity of the recipients. These implants have a tendency towards early aseptic loosening and failure in younger patients. With increasing life expectancy, longer periods of use have become inevitable in older patients. Surgical navigation systems, allow surgeons to position the implants more accurately and reproducibly, and they also record quantitative information such as joint range of motion, laxity, and kinematics intra-operatively, and have the potential to address three main challenges for total knee replacement: i) ensuring excellent and consistent outcomes, ii) treating younger and more physically active patients, and iii) enabling less invasive surgery.[16]

Robot assisted orthopaedic surgery has the potential for improving outcomes in arthroplasty. A type of robotic system for unicondylar knee replacement, The Robotic Arm Interactive Orthopaedic System (RIO) (MAKO Surgical Corp., Fort Lauderdale, Florida), uses pre-operative CT scans to create a three-dimensional (3D) computerised model of the patient's knee. The surgeon uses this model pre-operatively to plan the sizing and placement of the components. Intra-operatively, the surgeon will reference the bony surfaces of the femur and tibia, allowing the pre-operative model to be 'merged' with the actual anatomy of the knee.

The main disadvantage of using a navigation system to characterize knee kinematics is that the data are acquired under passive manipulation. Knee kinematics during activities of daily living could be different from those measured passively because of the high forces generated by muscles and by interactions with the external environment. Future research should define the relationship between the passive kinematics measured in the operating room and the post-operative active kinematics recorded with gait analysis[17]

Total hip arthroplasty is a commonly performed procedure in orthopaedics and trauma. The indications include intractable pain due to degenerative joint disease, pain and stiffness as a result of joint destruction from avascular necrosis, and developmental disease, especially Developmental Dysplasia of the Hip (DDH), later complications of Perthes disease and Slipped Capital Femoral Epiphyses (SUFE).

The factors in the successful implementation of total hip arthroplasty are the proper orientation of the acetabular component of an appropriate size for the patient, coupled with the implantation of a femoral stem that is of adequate neck length, offset and carried out with preservation of adequate tissue tension engendered by meticulous dissection. In preparing a total hip replacement an orthopaedic surgeon carefully selects an implant from the various types of currently available commercial hip implants with several 2D anterior–posterior (AP) X-ray images of the pelvis and the femur. The two-dimensional (2D) geometric features of plain X-ray films that are used to find a rough match between images of the associated bone and the implants lack accuracy within the framework of 3D planning environment. Jun and Choi[18] proposed a software system that designs a patient-specific hip implant by investigating the 3D anatomical geometry of the patient's hip joints because bone cutting and alignment have to be achieved in 3D planes in the surgical operation.

The major technical challenge of the proposed system is in extracting some typical 3D geometry parameters with respect to the patient's 3D bone anatomy and creating a patient-specific hip implant based upon the extracted parameters. The associated parameters include the femoral shaft isthmus, the anatomical femoral axis, the femoral head centre/radius, the head offset length, the femoral neck, the neck shaft angle, ante version, and the canal flare index (CFI). Some of these parameters are semi-automatically recognised and extracted, but others must be determined with the surgeon's intervention. The proposed system seems a practical alternative to the conventional process, but a more detailed validation process is necessary before clinical use.

Bone tumour surgery and deformity correction

It is believed that 3D modelling will have beneficial use in the preoperative planning for spinal deformity correction and for some radical surgical procedures for infection and tumour management.

Bone tumours are relatively uncommon compared to other organ systems in the body. For benign bone tumours the goal of treatment is excision if indicated, especially if the tumours suddenly become symptomatic or for cosmetic reasons. Some benign bone tumours may exhibit a tendency to malignant transformation, and early excision may be a routine treatment. Primary malignant lesions metastasize early. The goal of treatment following biopsy confirmation of the diagnosis is wide excision in combination with some chemotherapy regime.

The surgery to excise a malignant tumour must be carefully executed to preserve the limb unlike in the past when limb ablation was the procedure that was possible. Three-dimensional (3D) modelling can be utilised for surgical planning to make the tumour excision easier and more successful with respect to tumour recurrence. The VIRTOPS (VIRTual operation planning in Orthopaedic Surgery), system supports the preoperative planning of interventions in bone tumour surgery and the optimised design of individually adapted implants. It enables a complete virtual planning and simulation of operations in 3D virtual bodies. During the planning and construction process, the system is used by surgeons and technicians. The main task of the surgeon is to define the position and orientation of an optimal cutting plane.[19]

The challenges of 3D modelling are in the complexity of the image production which must go through several stages. Computed tomography (CT) scanning lends itself to easier image acquisition over magnetic resonance imaging (MRI), but the radiation to which the patient is exposed makes 3D image acquisition unattractive, especially in lesions in which surgeons have been known to perform with satisfactory outcome using routine X-ray.

In spite of some limitations, a patient-specific 3D surface model can be reconstructed automatically from a planar radiograph image when volumetric data is not available, and the reconstructed geometry can be used in a number of orthopaedic applications.[20]

The future

Three-dimensional (3D) modelling as a regular tool in surgical planning for orthopaedics and trauma will evolve because the visual products derived from its processes approximate more closely to the regular anatomy than the conventional plain X-ray, making treatment outcomes more predictable. The constant search by surgeons to implant prostheses that will last longer for young patients, to excise malignant tumours with a completely sterile bed and to correct deformities with gratifying result for patients will drive more research and innovation.

The ultimate goal seems to be the development of an imaging facility that is capable of integration of all of the 3D processes, such that one touch of a button will produce the desired image at an affordable cost and negligible hazard.

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