

Computer- and Robot-assisted Resection and Reconstruction of Pelvic Bone Tumours – A Review

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Abstract

Treating bone tumours within the pelvis is challenging due to the complex 3D geometry of the pelvic bone and the proximity of numerous organs and delicate structures. Pelvic bone tumours can be resected and reconstructed with bone allografts; such interventions require good cutting accuracy. This article provides a short review of the current developments in computer and robot assistance technologies integrated with pelvic bone tumour resection and reconstruction. Since the 1990s, there has been substantial development of intra-operative navigation systems. For bone tumour surgery, the majority of these systems are based on pre-operative planning using a 3D virtual model of the patient. Navigation consists of guiding tumour resection by providing surgeons with useful 3D information about the position of the surgical tools relative to the surgical site. At the present time, there exists only one clinical case report of a navigated pelvic tumour resection combined with a navigated allograft reconstruction. Finally, no studies have yet been published on robot-assisted pelvic tumour resection and reconstruction.

Keywords

Tumour resection, pelvic reconstruction, pre-operative planning, surgical navigation, surgical robotics, accuracy evaluation

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The surgical treatment of malignant bone tumours within the pelvis is challenging due to the complex 3D geometry of the pelvic bone and the proximity of numerous organs and delicate structures (mainly vessels, bladder, rectum and sciatic nerve).¹ Tumour resection with an adequate margin is necessary to minimise the risk of local recurrence.^{2–4} Local recurrence rates from 28% to 35% have been reported after limb-salvage procedures for pelvic tumours.⁵

Surgeons generally use anatomical pelvic landmarks to define the cutting planes all around the tumour with an adequate margin. These landmarks are based on computed tomography (CT) scanner slices, which are 2D representations of a 3D object. Thus, the main sources of error are scanning, defining the tumour extent, planning resection planes and, finally, performing the bone cuts.

In our own setting we conducted an experimental study where pelvic bone tumour resection was simulated⁶ and we demonstrated an insufficient geometrical accuracy with the conventional cutting procedure. The experiments were performed on simulated bones by experienced surgeons. Under ideal working conditions, the probability that a surgeon would achieve a 5mm tolerance on the desired cut was estimated to be 52% (95% confidence interval (CI): 37–67%).

The geometrical complexity and the restricted working space of the pelvic architecture aggravate the error arising from hand-controlled positioning of the surgical tool.

Several reconstruction methods exist. Reconstruction with osseous allograft presents some technical advantages. They can be shaped (cut) to perfectly fit the pelvic defect caused by the resection. Moreover, they allow good reinsertion of soft tissues like tendons and muscles. Finally, they provide true anatomical restoration of the complex 3D architecture of the pelvis.⁵

Non-union and fracture are both major complications using allografts. Many studies have already dealt with these clinical outcomes;^{6–12} however, ranges of the reported rates are large. Delloye et al.⁵ stated that the reported complication rate can be high, ranging from 30–90% in series ranging in size from nine to 96 patients, when excision of a pelvic tumour and reconstruction are combined in one procedure. Finally, Enneking et al.¹³ proposed some guidelines in order to promote rapid bone union: (i) to have precise and intimate contact between graft and pelvis; and (ii) to ensure gaps less than 4mm at each host-graft junction.

Coping with both the complexity and frequency of surgical interventions involving bone cutting, computer and robot assistance technologies have been extensively developed since the 1990s with the main objective of improving clinical and functional outcomes through increased accuracy and repeatability.^{14,15} Nowadays, several surgical navigation systems and active or passive robots are undergoing clinical trials or are already in use for procedures such as knee arthroplasty,^{15–18} high tibial open wedge osteotomy,^{19–21}

periacetabular osteotomy,^{22,23} tumour resection and reconstruction,^{24,25} craniotomy²⁶ and maxillofacial osteotomy.²⁷

The objective of this article is thus to provide a short review of the current developments and results in computer and robot assistance technologies integrated with surgical procedures involving bone cutting, and particularly in the specific application of pelvic tumour surgery. We can distinguish four types of technological assistance for the cutting of bones: pre-operative assistance called “pre-operative planning”, and three intra-operative assistances that we call “surgical navigation”, “rapid prototyping guidance” and “surgical robotics”.

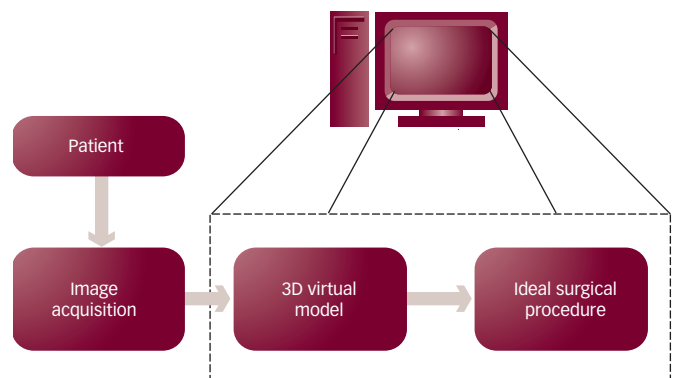
Pre-operative Planning and Registration

Planning consists of defining the ideal surgical procedure. For pelvic bone tumour surgery, it consists of defining both the ideal tumour resection to minimise the risk of local recurrence and the optimal reconstruction by bone grafts to ensure precise and intimate contacts between graft and pelvis. The first step is the acquisition of a virtual model of the patient using a medical imaging technique (see Figure 1). The CT scan is widely used because it allows clear distinction between bony structures and soft tissues. Magnetic resonance imaging (MRI) is also used because it enables accurate delineation of a disease, such as the extension of a bone sarcoma within soft tissues. Moreover, imaging techniques allow acquisition of a virtual model of the patient in three dimensions using algorithms of segmentation and reconstruction. Thanks to recent developments, the desired resection planes can now be defined on a virtual 3D model of the patient.²⁸ Moreover, selection of the best-fitting allograft can be performed using a CT-based registration algorithm between the patient and the available pelvic allografts.²⁹ The criterion of selection is the best geometrical congruency of the two CT volumes (the 3D CT of the patient and the 3D CT of the allograft). When the optimal allograft is chosen, the CT–CT registration result enables the definition of cutting planes of the graft that are identical to the cutting planes around the tumour.

When the ideal cuts are planned using the virtual 3D model of the patient, we have to transfer this planning to the real patient;³⁰ this step is called “registration” and is physically performed in the operating room. The most common procedure consists of acquiring geometrical or anatomical information on the bony structures of the patient and retrieving the same information within the virtual model of the patient. In practice, we will determine sensor points on the bone surface and compute the optimal positioning of these points on the surface of the virtual model (see Figure 2). The optimal position is usually computed by the method of least squares and defined as the overall position that minimises the sum of the squares of the distances between the acquired points and the virtual surface.³¹ The acquired points can be: (i) clouds of points acquired randomly on the bone surfaces (surface-based registration); (ii) specific anatomical landmarks (point-based registration); or (iii) geometrical points defined by markers (marker-based registration) that were positioned before the medical imaging and visible in the virtual model of the patient.³² A recent experimental study has assessed a global surface-based registration accuracy of 1.3mm during simulated pelvic tumour surgery.³³

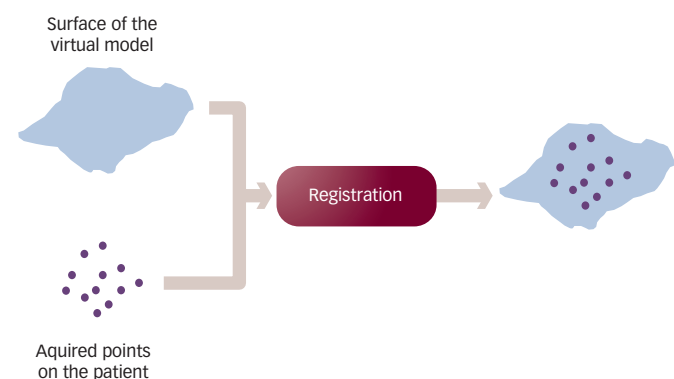
There exist other registration techniques. The bone-morphing registration method, based on statistical models,³⁴ does not use pre-operative imaging to construct the virtual model of the patient: both registration and planning are performed intra-operatively.

Figure 1: Pre-operative Planning



The ideal surgical procedure is defined using a virtual 3D model of the patient. The virtual 3D model is constructed from 2D medical images.

Figure 2: Registration

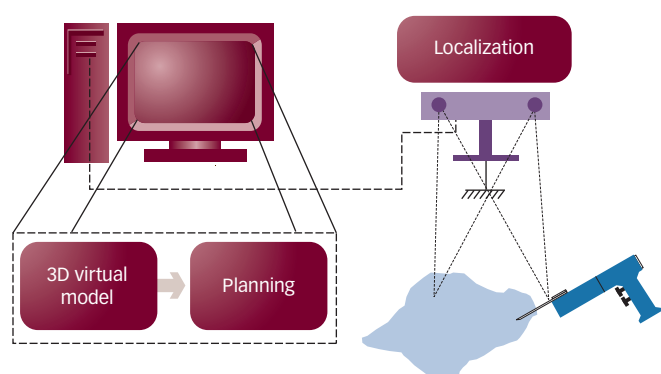


Geometric or anatomic information (black points) is acquired on the patient. The corresponding information is retrieved on the surface of the virtual model. Registration results in a geometric mapping between the patient and the virtual model.

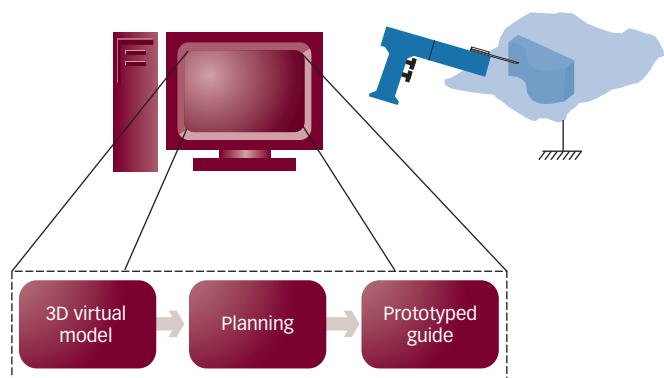
Clouds of points are first acquired on the patient’s bone surfaces, and a virtual statistical model is then deformed to best fit these acquired points. The virtual model is a mean model (from a statistical point of view) that is representative of the population. However, this technique is not used for pelvic bone tumour surgery for two reasons: first, bone tumours within the pelvis have unpredictable 3D geometries, thus it would be difficult to construct a statistical model of a “mean” pelvic tumour; and second, bone tumours cannot be palpated. It is impossible to acquire clouds of points on the tumour surface to perform the registration with a statistical mean model.

The ultrasound registration method³⁵ consists of acquiring anatomical information by manipulating an ultrasound probe. The registration of this information can then be performed using a pre-operative virtual 3D model (constructed pre-operatively by using standard medical imaging) or using a statistical model. The main advantage is that the method is non-invasive: it does not require physical palpation of the bone surfaces because the ultrasonic probe can be manipulated ‘remotely’. The feasibility of using this technique with a global accuracy of around 1mm for pelvic surgery was recently demonstrated by Oszward et al.³⁶

The fluoroscopy registration method^{21,37,38} does not require pre-operative medical imaging. The fluoroscope is a transportable device, commonly available in operating rooms, that enables the acquisition of intra-operative radiographs of the patient. The

Figure 3: Surgical Navigation

The localiser detects the surgical tools. Both position and orientation of the detected tools are displayed in realtime in the virtual model of the patient.

Figure 4: Rapid Prototyping Guidance

The patient-specific cutting guide is designed in the virtual model of the patient. The guide is manually positioned on the bone surface of the model.

fluoroscope is a semi-circular arm equipped with an X-ray transmitter and receiver. The method consists of taking radiographs of the bony structures under different orientations and registering these images using a navigation system.

Surgical Navigation

Intra-operative navigation (see *Figure 3*) consists of localising the surgical tools manipulated by the surgeon within the operating field and displaying in realtime the position and orientation of these tools in the virtual model of the patient.^{15,39} There are three types of device enabling the localisation of objects in realtime.

- Optical navigation systems localise the position and orientation of markers that are rigidly fixed to the surgical tools and patient.^{40,41} The markers have to be visible in the workspace of the localiser, which requires a free line of sight between the localiser and the markers. It may be a localiser that transmits and receives infrared (the markers reflect part of the infrared emitted by the localiser); a localiser that only receives infrared (the markers themselves emit infrared); or a 'video' localiser (the markers are made of black and white patterns that are identified by the localiser through video images).
- Electromagnetic navigation systems also localise the position and orientation of markers attached to the tools and patient.⁴² The markers emit electromagnetic waves that are detected by the localiser. There is no requirement for a free line of sight between

the markers and the localiser. However, each marker has to be connected by electrical cables that may obstruct the surgical field. Finally, there is also a risk of magnetic interference with other electrical devices present in the operating room.

- Mechanical navigation systems directly localise the position and orientation of the surgical tools and patient by using passive mechanical arms.^{43,44} These arms are equipped with angular position encoders, typically one rotation sensor at each articulation. The method consists of localising the tip position of these arms and computing the position and orientation of the surgical tools relative to the patient. The main disadvantage of the mechanical systems is that they can significantly obstruct the operative field.

Besides localising the surgical tools within the operative field, all these systems can also be used during the registration step to detect the manipulation of a sensor tool or an ultrasound probe, or to localise the position of a fluoroscope acquiring intra-operative radiographs of the patient. The only requirement is to equip the tools, probes or fluoroscopes with adequate markers. Moreover, we have to keep in mind that the existing navigation systems rarely have an accuracy of <0.3mm, especially because of the localiser resolution.

There are several ways (from a technological point of view) of integrating a navigation system with a surgical procedure involving bone cutting.

- Navigated rod placement⁴⁵ – During knee arthroplasty, functional instrumentation consists of rigid rods whose ends are fixed to the centres of rotation of the hip, knee and ankle in order to define the mechanical axis of the leg. Surgeons position these rods with the aid of a navigation system and then manually position and fix a cutting guide to these rods and perform the bone cuts by inserting the cutting tool into the guide slot. This technique demonstrated improved post-operative radiographic alignment without increased short-term complications.
- Navigated pin placement for a pin-guided cutting block⁴⁴ – The cutting guide is attached to the bone with pins. Surgeons first insert the pins into the bone with the aid of a navigation system. Then they manually position the cutting block onto the pins and perform the bone cuts by inserting the cutting tool into the guide slot. Despite the feasibility, which was experimentally shown, this technique, using a visual display for pin placement, can be found to be difficult and time consuming.
- Navigated placement of a cutting guide^{46,47} – Surgeons position the cutting guide on the bone with the aid of a navigation system. Then they manually insert the pins that rigidly fix the cutting guide to the bone surface and perform the bone cuts by inserting the cutting tool into the guide slot. This technique demonstrated very good results in terms of implant positioning.
- Navigated manipulation of a cutting tool⁴⁸⁻⁵⁰ – Surgeons perform bone cutting under direct manipulation of a cutting tool with the aid of a navigation system. The cutting tool is navigated by means of markers attached to it and detected by the localiser. Haider et al.⁴⁹ and Ferrol et al.⁵⁰ showed the feasibility of performing navigated cutting with an oscillating saw during simulated knee arthroplasties and craniotomies, respectively. In our own settings, we assessed a geometrical accuracy of 2.8mm using a navigated oscillating saw to perform cutting on a simulated bone model.⁴⁸

Finally, there are several examples of navigated surgery for bone tumours in general and especially for pelvic tumours. All these examples have shown the clinical feasibility of achieving tumour-free resection margins.

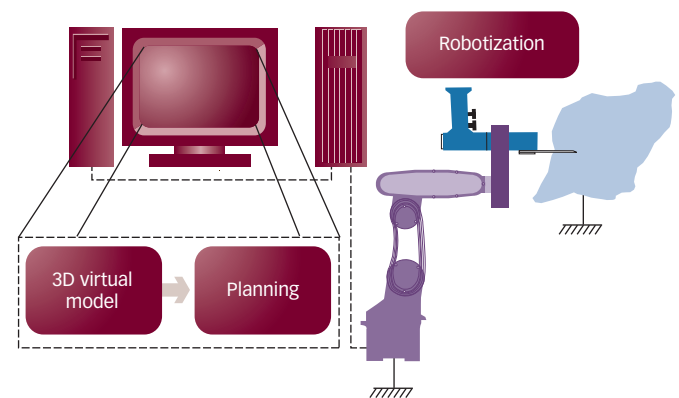
- Tumour resection with a navigated burr^{51,52} – The tumour resection is performed with a surgical burr. The navigation system is used to localise the cutting tool that is manipulated around the tumour. In practice, the localiser detects both the tip of the tool and its main axis (the rotation axis of the burr).
- Tumour resection with a navigated drill or diathermy^{25,53} – The surgical drill is navigated to insert pins along the trajectory (the path) of the tumour resection. Surgeons then perform the cuts under visual guidance of the position and orientation of the pins. The surgical diathermy is navigated to draw the resection path directly onto the bone surface. Surgeons therefore perform the cuts along the line drawn.
- Pelvic tumour resection with a navigated chisel⁵⁴ – The navigation of a surgical chisel to resect a tumour is identical to the navigation of a burr. The localiser detects the tip of the chisel and its main axis. Historically, the chisel was the first tool to be navigated to perform bone cutting and the application was the surgical treatment of periacetabular dysplasia.²³ More recently, Fehlberg et al.⁵⁵ assessed a median deviation of 3.3mm between the planned and the performed bone cuts.
- Pelvic tumour resection and reconstruction with a navigated oscillating saw⁵⁶ – The oscillating saw is navigated to perform the cutting around the tumour and on the selected allograft without the use of a cutting guide. The oscillating saw differs from the other cutting tools by the fact that we have to navigate the saw blade within a plane (the oscillation plane of the blade) and not along only one axis (the rotational axis of a burr or a drill). This is the first clinical case in which both tumoural resection and reconstruction by allograft were performed with the aid of a navigation system during the same surgical intervention. Post-operative radiographs showed excellent fitting of the allograft to the pelvis.

To our knowledge, navigation of a cutting guide has never been applied to tumour resection and reconstruction within the pelvis. Such guidance apparatus does not exist for pelvic tumour surgery. We think that the main reasons are (i) the geometrical complexity and the restricted working space of the pelvic architecture; and (ii) the fact that bone tumours within the pelvis have unpredictable 3D geometries.

Rapid Prototyping Guidance

Rapid prototyping guidance (see *Figure 4*) comprises performing the bone cuts using patient-specific cutting guides.^{57,58} These guides are designed and manufactured under computer assistance using a virtual model of the patient. Because such a prototyped guide is theoretically shaped to match the bone surface of the patient, its positioning onto the bone surface is assumed to be unique and well defined. Consequently, navigation of such a guide is not required. However, the surface of the bone structure being cut has to be cleared to correspond as closely as possible with the virtual surface on which the guide has been designed and manufactured. Moreover, since the guide is in direct contact with the bone surface of the patient, the materials used in its manufacture have to be sterilisable. For bone tumour surgery, the main problem in designing a patient-specific guide is the clinically unsuitable direct contact between the

Figure 5: Robot-assisted Cutting



The cutting tool is attached to the end-effector of a robotic device. The robot controls the manipulation of the cutting tool in accordance with the planning.

tumour and the guide: there would be a high risk of contaminating other anatomical sites of the patient. To our knowledge, rapid prototyping guidance has never been applied to tumour resection and reconstruction within the pelvis.

Surgical Robotics

Robot-assisted bone cutting (see *Figure 5*) consists of automating the surgical gesture of bone cutting (completely or partially). There exist several articles in medical robotics, including surgical robotics.^{14,59–61} Each of these articles emphasises the complexity of integrating a robotic device with a surgical procedure. The main factors impeding the clinical integration of a robot are: (i) the lack of significant evidence of the added value of the robot-assisted procedure; (ii) the feeling of insecurity caused by the absence of a surgeon at some specific stages of the robot-assisted procedure; and (iii) the complexity of adapting a standard surgical procedure to a new technology.

As for navigation, there exist several examples of integration of a robot-assisted device with a surgical procedure involving bone cutting, especially for knee and hip applications.

- Active positioning of a cutting guide^{18,62,63} – The robot is positioned on the ground or mounted directly on the bone structure being cut. After the registration step, the robot controls a cutting guide in the desired position and orientation according to pre-operative planning. The surgeon then performs the cuts by manually inserting a saw blade into the slot of the cutting guide. By controlling the positioning of the cutting guide (and not the manipulation of the saw), the robot does not act directly on the patient. The advantage of this robot-assisted procedure relies on an accurate and repeatable positioning of the guide according to pre-operative planning. The advantage of a robot directly fixed to the bone is the immobilisation of the cutting guide relative to the bone structure being cut (hypothesising an ideal stiffness of the robot mechanical structure). Finally, the main sources of error are setting up the robot according to the bone structure, relative motions between the cutting guide and the bone (in the case of a robot positioned on the ground) and, finally, the clearance of the saw blade inside the guide slot.
- Active positioning of a milling guide¹⁸ – The robot is directly attached to the bone and controls the guide in the desired position and orientation. The surgeon then performs bone milling by manually

inserting the burr into the guide. Again, as for the positioning of a cutting guide, the advantage of such a robot-assisted solution is an accurate and repeatable positioning of the milling guide according to pre-operative planning. Fixing the robot to the bone prevents patient motion relative to the robot. Finally, the main sources of error are setting up the robot according to the bone structure and the clearance of the milling tool inside the guide.

- Active cutting and milling^{17,26,48,64–68} – The robotic devices are programmed to actively control the trajectory of the cutting or milling tool according to pre-operative planning (the desired path). The surgeon therefore plays the role of supervisor, controlling normal starting and stopping cutting procedures and emergency stops. The main source of error is setting up the robot according to the bone structure being cut or milled. The advantage of actively controlling the bone cutting or milling is the accuracy and the repeatability that the robot can provide. Milling with a burr enables better surface roughness during bone resurfacing interventions compared with cutting with an oscillating saw. Milling also enables more complex paths of osteotomies than surgeons are capable of performing with an oscillating saw.

In our own setting, we assessed a geometrical accuracy of 1.7mm using an active robotic process to perform cutting with an oscillating saw on a simulated bone model.⁴⁸ This was significantly better accuracy when compared with a navigated cutting process (2.8mm, $p < 0.0001$) and a freehand cutting process (5.2mm, $p < 0.0001$).

- Semi-active milling^{16,69–74} – The robotic devices are used under a milling co-manipulation scheme. Co-operation between surgeon and robot is programmed to constrain the manipulation of the milling tool by the surgeon. The robot plays the role of an assistant that prevents milling along undesired paths. This solution has all the benefits associated with active milling but also provides the surgeon with greater control of the milling process. The main challenges of this technology are related to the manipulability and transparency of the robotic arm during the co-manipulated milling process.

Conclusions

As evidenced by numerous examples in the current literature, there has been, since the 1990s, substantial development of computer assistance technologies to improve the outcomes of pelvic bone tumour surgery. The majority of the available systems are based on pre-operative planning using a 3D virtual model of the patient. Navigation consists of guiding tumour resection by providing surgeons with useful 3D information about the position of the surgical tools relative to the surgical site. Nevertheless, few efforts have been made to develop computer-assisted tools for the reconstruction step with a bone allograft: there is only one example of computer-based

selection of the best pelvic allograft,²⁹ and there is only one clinical case report of a navigated pelvic tumour resection combined with a navigated allograft reconstruction.⁵⁶

Again, according to the literature, we can assess that, at the present time, no studies have been published on robot-assisted pelvic tumour resection and reconstruction. However, the experimental results that we achieved on a simulated bone model⁴⁸ are a promising first step towards developing and validating a robot-assisted device for pelvic bone tumour resection and reconstruction. Finally, when developing new assistance technologies for medical applications such as orthopaedic interventions, we should keep in mind that these technologies still have one major drawback: numerous studies fail to prove their real added value. For instance, for total knee arthroplasty (which is the most important application of computer- and robot-assisted technologies dedicated to orthopaedic surgery), there is still some debate as to whether the prosthesis alignments are improved with the use of a navigation system.^{15,75}

Due to the multidisciplinary aspects of computer- and robot-assisted systems, the scientific community reached the logical conclusion that a more objective evaluation was necessary, and that there is a need for defining new evaluation standards for assessing the accuracy of such technologies. A first work originated with the Computer Assisted Orthopaedic Surgery (CAOS) society in conjunction with the American Society for Testing and Materials (ASTM). In 2004, these groups undertook the creation of an ASTM standard for assessing the accuracy of CAOS systems.^{76,77} However, this ASTM standard is still in progress. More recently, some authors proposed purely geometrical evaluation methodologies. Barrera et al.⁷⁸ designed an evaluation method of bone cuts in total knee replacement based on purely geometrical indices quantifying the differences between the cut planes and the desired planes. In our own settings, we designed a new evaluation methodology⁷⁹ that is based on the International Organization for Standardization (ISO) 1101:2004 standard. We validated the use of an ISO-based parameter called 'location' for evaluating bone cutting accuracy regardless of the cutting process. Finally, Pearle et al.⁸⁰ proposed an interesting evaluation methodology that is very close to the ISO philosophy:

"The quantification of important components of a surgical procedure introduces manufacturing concepts into the art of orthopaedic surgery. Importantly, discrete technical specifications must be assigned to various procedures to make quantitative orthopaedic surgery relevant. In establishing the specifications, we have to understand (1) the target value for the specification; (2) the tolerances of the specification; (3) whether computer-assisted surgery tools are reliable (accurate and precise) in achieving the technical specification; and (4) whether the specification is clinically relevant." ⁿ

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