Robots and Tools for Remodelling Bone

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Abstract – The field of robotic surgery has progressed from small teams of researchers repurposing industrial robots, to a competitive and highly innovative subsection of the medical device industry. Surgical robots allow surgeons to perform tasks with greater ease, accuracy, or safety, and fall under one of four levels of autonomy; active, semi-active, passive, and remote manipulator. The increased accuracy afforded by surgical robots has allowed for cementless hip arthroplasty, improved postoperative alignment following knee arthroplasty, and reduced duration of intraoperative fluoroscopy among other benefits. Cutting of bone has historically used tools such as hand saws and drills, with other elaborate cutting tools now used routinely to remodel bone. Improvements in cutting accuracy and additional options for safety and monitoring during surgery give robotic surgeries some advantages over conventional techniques. This paper aims to provide an overview of current robots and tools with a common target tissue of bone, proposes a new process for defining the level of autonomy for a surgical robot, and examines future directions in robotic surgery.

Keywords—Orthopaedics, surgical robotics, bone remodeling, arthroplasty, robot-assisted neurosurgery, robot-assisted spine surgery, autonomous surgery,

I. Introduction

Remodeling and resection of bone is a delicate and complicated process, and until recently, bone cutting was performed ‘intuitively’ rather than ‘technically’ [1]. Historically, bone remodeling procedures have used tools similar to those of a carpenter, such as hand saws, drills, and chisels [2], with evidence of cranial trephination osteotomies from thousands of years ago [3]. Previously these tools were wholly manipulated by skilled surgeons, aiming to remodel the bone and cause as little damage as possible, however since the mid-1980’s, surgical tools and equipment have been steadily integrated with robots in the operating theatre. With close to 40 years of experimentation, the field of robotic surgery has progressed from small teams of researchers repurposing industrial robots, to a competitive and highly innovative subsection of the medical device industry. Similarly, bone cutting tools are the subject of significant research, ranging from improved performance for standard cutting tools, as well as the development of technologically advanced methods.

A number of review papers have attempted to encompass the entire current state of surgical robotics [4], as well as the generational changes of robots [5]. Others have focused on the robots used specifically for arthroplasty [6] or neurosurgery [7], however a number of recent applications are distinct from orthopaedics or spinal surgery. Two such examples include systems for automated cochlea implantation [8] as well as a novel process for performing craniomaxillofacial surgeries [9]. Despite the differences in application, a commonality exists between many of these robots, that being the target tissue of bone.

An old adage states “a tradesman is only as good as their tools”. A skilled operator requires precision tools to be effective, and precision tools are only effective when used by a skilled operator. When considering a surgical robot as a tradesman, it stands to reason that a discussion on their benefits necessitates an examination of the tools available to them. Thus, this paper encompasses a spectrum of commercial and experimental surgical robots used for precise remodeling of bone, in addition to the tools available while investigating how these overlap and interact. The work aims to provide a comprehensive overview of current tools available to surgeons for bone remodeling, including analysis of the capabilities of each system and approach and a look towards the future of the field.

II. Classification of Surgical Robots

A. Surgical robots

The initial drive for robotics in surgery was to improve process. Fundamentally, surgical robots are simply another tool to allow surgeons and medical professionals to perform tasks with greater ease, accuracy, or safety. Medical procedures involving surgical robots use terms such as Robotic Surgery, Robot Assisted Surgery, Haptic Robot Assisted Surgery, Computer Navigated Surgery, Computer Assisted Surgery (CAS), and Computer Aided Surgery, which are used almost interchangeably (although Computer Navigated, Aided, and Assisted surgeries often only include a tool tracking / guidance system and may lack a surgical robot). More specific terms are used depending on the medical discipline employing the technology, e.g., Computer Assisted Orthopaedic Surgery (CAOS).

B. Surgical Navigation

Before a surgical robot can interact with a patient, the robot must know the position and orientation of the patient. Both patient location and orientation can be ascertained by mechanically connecting the robot with rigid linkages or frames, [5], [10], however this information is now more commonly obtained through navigation systems. The most common approach to surgical navigation is optical tracking, whereby camera systems monitor the position and orientation of markers attached to set pieces within the operating room

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(OR) (e.g., tooling, robotic arm, patient) [11]. The relative positioning of these markers is obtained through registration. The goal of registration is to combine the location information from one or more imaging modalities with the location of the patient in the OR, such that the virtual data and the patient share a common coordinate space [12]. Registration can be either marker-based, or marker-free. Marker-based registration requires markers to be visible in preoperative images, which can then be located on the patient during the procedure. Examples of marker-based registration include markers glued to the skin, or percutaneous bone screws. In comparison, marker-free registration relies on the inherent patient anatomy, such that boney protrusions serve as natural identifiers of location. Marker-free registration can be further categorized into point matching, surface matching, and image matching. Point matching is used as an initial step in registration, where specific points of anatomy are used as landmarks to match with the patient image data.

Navigation can be performed with or without preoperative images [13]. In image-guided surgery systems, bone geometry is acquired from preoperative imaging, often Computed Tomography (CT), or intraoperative images (typically fluoroscopy). These imaging modalities allow registration between the patient and the navigation system, such that the location and anatomy of the patient becomes known to the robot. For image-free surgery, an initial 'default' virtual model of the target joint / bone is morphed to match the patient's physical anatomy, by the surgeon contacting anatomical reference points with a special tool tracked by the navigation system. This morphed virtual model provides guidance to the surgical team [14].

Surgical navigation systems provide some of the functionality of a robotic platform with or without the provided automation [15]. For the latter case, these systems provide real-time feedback of tool position and orientation relative to the patient, however are still reliant on the surgeon to carry out the procedure based on this feedback. Many of the principles associated with surgical navigation (pre-operative planning, image-patient registration, intra-operative feedback) are shared with robotic systems.

C. *Levels of Autonomy*

The term 'autonomy' is generally associated with the idea of a system functioning on its own to perform a given task. A significant factor determining the level of autonomy for any robot is the feedback between the system and the environment. To perform a task, a robot must know its location within the environment (external state) and its own position and orientation (internal state) [16]. External state information is obtained from equipment such as optical or electromagnetic tracking systems, while internal state information is determined by the robot itself (e.g., joint angles, force-torque sensors). The manipulation required from the internal state to perform a task autonomously is set during planning. Surgical robots fall under one of four levels of autonomy; active, semi-active, passive, and remote manipulator. While the current classifications of 'active' and 'remote manipulator' robots are relatively straightforward ('active' robots are most autonomous, 'remote manipulators' are least autonomous), the separation between 'passive' and 'semi-active' robots is somewhat poorly defined. There is a general consensus that a passive robot is one which has no direct involvement in performing a surgical task, however inconsistencies exist in what is considered "performing a surgical task", and some researchers feel this means the robot must not touch the patient, support the cutting tool, be handled by the surgeon, or dynamically interact with the surgeon and the environment [5], [17]–[19]. These restrictions effectively make the 'passive' classification reserved for navigation and guidance systems due to their complete lack of physical interaction with a patient, cutting tools, and the surgeon. In this paper, a revision to the definitions of the four levels of autonomy for a surgical robot is proposed, which is used for definitions of autonomy for the remainder of this paper. This new definition is shown in Fig. 1.

A yes/no answer to each question determines which class any robot belongs to; 'Yes' to question 1 classifies the robot as a remote manipulator; 'Yes' to question 2 classifies the robot as passive; 'Yes' to question 3 classifies the robot as semi-active ('No' to question 3 classifies the robot as active). To explicitly clarify potential ambiguities under this definition; 'dexterous input' means considered, precision movements from the user, with the intention of reaching or affecting an exact area of tissue with the tool. It does not mean manually repositioning or aligning the robot prior to using the tool, or moving the cutting tool along the cutting path, as with semi-active robots.

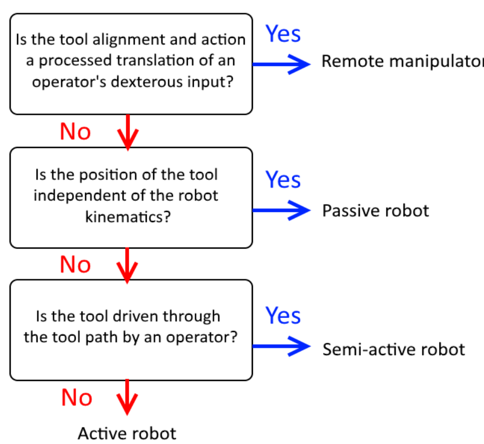

Fig. 1. Proposed flowchart to determine level of autonomy for a generic robotic system.

1) *Remote Manipulator*

Remote manipulators (also referred to as telesurgical systems) allow surgeons to perform intricate tasks in areas with limited access. A significant advantage of telesurgical systems is the scaling of a surgeons motion, i.e. the limits of human dexterity are mitigated through robotic control of miniaturized tooling. Arguably the most well-known example of remote manipulators is the Da Vinci (Fig. 2), which allows precise excision and suturing operations with rigid robotic arms, remotely controlled by a surgeon from a separate console [20]. In general, remote manipulators receive a surgeon's dexterous input, then translate, scale, and reproduce the actions and motions at the robotic arms of the system. A similar remote manipulator system is RAVEN, a cable-actuated 7-degrees-of-

Fig. 2. The DaVinci can be classified as a tele-manipulator system in which direct input motion from the surgeon is filtered and scaled. It is widely used in soft tissue surgery in a number of fields [111].

freedom (DOF) system used for minimally invasive surgeries [21]. Remote manipulators typically provide the surgeon with a real-time view of the surgical site via footage obtained from endoscopes, with standard medical imaging (radiography, magnetic resonance) used more in the preoperative planning. Remote manipulators are not commonly used for surgery on bone however Da Vinci has been used for cadaveric hip [22] and shoulder [23] arthroplasty, and skull base procedures such as mastoidectomy [24].

2) Passive Robotic Systems

Passive systems can be thought of as a tool guide or steady to assist with surgical accuracy, but not a navigation system per se. As an example, one of the earliest robotic surgical procedures used an Unimation PUMA 200 to align a stereotactic surgical needle to within one millimetre of the required position [5], [10]. Once aligned, the robot was switched off, and the surgeon inserted the needle while the robot maintained alignment. As the surgeon was in control of the depth of the surgical needle, the position of the tool was independent of the robot's kinematics; as the tool is not permanently fixed to the robot, the robot is not performing the surgical aspect of the operation. Modern examples of passive robots used for bone remodelling procedures include iBlock (used as a tool guide in knee arthroplasty), and Mazor Renaissance (used for precise alignment of a drill in spinal and neurosurgery).

3) Semi-Active Robotic Systems

Semi-active robots can be thought of as an active robot manually driven through the cutting path by an operator. Semi-active robots still require cutting planes, tool-paths, or workspaces to be defined in a planning stage, however the positioning of the tool within the planned workspace is controlled by the surgeon. The robot itself usually provides haptic feedback to the operator when the cutting tool approaches or exceeds the edge of the workspace, and for some robots even stops the cutting action of the tool [25]. Semi-active systems are similar to remote manipulators in that the tool is driven by the operator, however the difference between the two classes is that a semi-active robot does not require both processing and translation of a dexterous input to move the tool tip during cutting operations. The MAKO system by Stryker is a well-known example of a semi-active surgical robot; while the surgeon maneuvers and operates the cutting tool, the MAKO robot keeps the tool aligned with the planned cutting plane and prevents the tool exceeding the desired region boundary.

4) Active Robotic Systems

Of the four levels of robot autonomy, active robots are the least reliant on control from an operator, but the most reliant on path planning. Active robots perform surgical tasks such as precision milling of the medullary cavity for a hip arthroplasty [26], or removal of bone cement in hip implant revision surgery [15]. Active robots often follow a pre-planned tool-path based on preoperative images, such that inside the operating theatre, the robot needs to be positioned with respect to the operating site, then precisely registered to the patient. Despite the high degree of autonomy, surgeons will directly supervise an active robot as any malfunction or path error could be catastrophic [27]. Examples of active surgical robots include CASPAR and ROBODOC, which initially require precise positioning in relation to the patient, and then cut the bone autonomously while the surgeon supervises the process.

III. Surgical Robots by Application Domain

A. Robots for Orthopaedics / Arthroplasty

One of the more established areas of surgical robotics is in reconstructive knee and hip surgery. Partial knee arthroplasty (PKA), total knee arthroplasty (TKA), and total hip arthroplasty (THA) are often performed on patients with osteoarthritis of the given joint, with the aid of a surgical robot. Both the longevity of the replacement components and a patient's satisfaction with the procedure depend on factors such as implant design, preoperative state of the joint, surgical technique, and rehabilitation program [28]. It is thought that the most common reason for failure of a TKA is the selected surgical technique [29]. The conventional manual technique involves cutting of bone and soft tissue balancing, with cutting planes aligned with anatomical landmarks to accommodate the geometry of the joint implant. Many PKA/TKA components are attached to the remaining structure using bone cement, however with more precise and accurate cutting paths, cementless fixation has become more prevalent. Cementless fixation uses implants with a porous surface structure to exploit the natural ingrowth of bone, leading to bone-to-metal integration, which is associated with a greater implant lifespan [30]. For cementless fixation to be viable, the gap between the implant and the remaining bone must be kept to a minimum. A number of studies [29], [31]–[33] have shown that postoperative pain, biomechanics, implant function and implant longevity can all be improved by returning the leg to optimal alignment, i.e., restoring the mechanical axis of the leg to neutral (defined as within 3 degrees of a straight line between the centre of the hip, the knee, and ankle). Conversely, complications such as implant instability and loosening, as well as malrotation and misalignment have been shown to be a result of surgical techniques which inadequately address soft tissue balancing [34], [35].

Robots greatly assist with arthroplasty procedures. As with most robotic surgeries, the general process involves generation of a patient model and appropriate plan, registering the patient to the model and plan, and using the robot to make cuts in accordance with the plan. There are a handful of surgical robots used in clinical settings for arthroplasty procedures, many of which have undergone changes to name, manufacturer, and owner since their inception.

CASPAR

CASPAR (Computer Assisted Surgical Planning And Robotics) (Fig. 3) was an active, image-guided robot used for THA and TKA, focused on decreasing the postoperative variability in the mechanical axis of the leg [6]. CASPAR was based on an RX90 6 axis industrial robot, by Stäubli [36]. Planning for CASPAR procedures required an initial separate surgery, in which bi-cortical bone screws were placed in the femur and tibia. These screws served as fiducial markers during a preoperative CT scan, which enabled the registration of the patient to the surgical plan. For THA procedures, the femoral cavity accepting the stem of the implant was accurately prepared by CASPAR, allowing for cementless implantation of components. CASPAR was acquired in 2000 by Getinge, then again in 2001 by Universal Robot Systems (URS), at which point it was discontinued [4].

Fig. 3. CASPAR was an active surgical robot system designed to optimize outcomes in orthopedic surgical procedures [112].

Acrobot / Sculptor RGA

Acrobot (Fig. 4) was a small, semi-active, lower-power, purpose-built robot for use in both PKA and TKA, and was largely developed at the Imperial College of London. The robotic component of Acrobot consisted of a smaller manipulator attached to a larger, six axis gross positioning robot [37]. The gross positioning robot was necessary as the manipulator component had a relatively small range of angles (+/-30°) and reach (30–50cm). The manipulator allowed motion in three orthogonal axes, equivalent to roll, pitch, and yaw. The initial planning process for Acrobot was similar to that used with CASPAR, where preoperatively placed fiducial markers were registered against the computer plan. A non-invasive registration method was also developed, where anatomical landmarks were matched to surface points in virtual space with an iterative closest point algorithm. Intraoperatively, a surgeon guided the manipulator while active constraint controls restricted the motion of the manipulator, allowing safe and accurate cuts to fit the TKA implant. Acrobot was acquired by Stanmore in 2010, later withdrawing from robotics in 2013 [6].

Fig. 4. The semi-active Acrobot system designed for partial and total knee arthroplasty procedures [4].

ROBODOC

The first robot to be used for orthopaedic surgery in a clinical setting, ROBODOC (Fig. 5) was initially developed to improve the femoral preparation of cementless THA procedures. ROBODOC is an active computer-aided bone milling system, used in conjunction with ORTHODOC planning software, which facilitates preoperative planning of both hip and knee arthroplasties with reconstructed three-dimensional (3D) CT images [27]. ROBODOC received approval from the United States Food and Drug Administration (FDA) in 2008, and has performed over 24,000 arthroplasties of both the hip and knee. For THA procedures, ROBODOC is limited to preparation of the femoral cavity, meaning the position and orientation of the acetabular cup is only able to be estimated with the anteversion of the femur after implantation.

Fig. 5. ROBODOC is an autonomous surgical robotic system robotic for hip and knee arthroplasty [27].

MAKO

Fig. 6. The Stryker MAKO system is widely used for partial and total knee, as well as total hip, arthroplasty procedures. It functions in a semi-active control mode [113].

Stryker's MAKO (Fig. 6) is a 6-DOF semi-active robot used for PKA, TKA, and THA [38], as well as experimental pre-clinical use in orthopaedic oncology [39]. MAKO received FDA clearance for PKA procedures in 2006, THA in 2010 [38], and TKA in 2015 [40]. During surgery, the cutting tool is held steady by the robot, while the surgeon guides and operates the tool within the constrained cutting zone, back-driving the motors and joints of the system. The MAKO arm functions as a haptic control with audio/visual feedback during sawing and milling operations, and pushes back on the surgeon to prevent cuts outside the planned resection planes. MAKO relies on CT images for preoperative planning of cutting planes, with the intraoperative registration process involving anatomical landmarks as well as surface points from the bone. MAKO does not require the bone to be fixed in space, as the navigation system dynamically accounts for the relative position of the bone, the tool, and the robot.

iBLOCK / PRAXITELES / PRAXIM / OMNIBOTICS / OMNI

Fig. 7. The iBlock system is a passive, bone-mounted robotic cutting guide used in total knee arthroplasty procedures [4].

iBlock (Fig. 7) is a passive, modular, bone-mounted robotic cutting guide for TKA. Imageless anatomic mapping is combined with computer-tracked infrared markers to generate a virtual model for navigation. The system consists of three primary components; a frame for fixation and adjustment of cutting plane alignment; a cutting guide for the blade / bur; and, a 2 degree-of-freedom actuation unit to move the cutting guide relative to the cutting plane fixation frame [41]. By mounting directly to the bone, iBlock compensates for any intraoperative motion of the limb. iBlock received FDA approval for use in TKA procedures in 2010 [28].

NAVIO PFS

Navio Precision Freehand Sculptor (PFS) (Fig. 8) is a semi-active freehand robotic sculptor for PKA and TKA, integrating CT imaging with imageless intraoperative registration to generate a virtual 3D model [28]. Unlike other surgical robots, Navio PFS is held entirely by the surgeon, with no mechanical positioning of the cutting tool. The robotic control aspect is within the cutting tool; when the cutting tool approaches the edge of the workspace, the cutting tool is slowed or retracted into the handpiece to prevent further removal of bone [42]. Navio PFS received FDA approval for PKA in 2012 [43].

Fig. 8. The Navio PFS is a handheld semi-active robotic system [111] used in partial and total knee arthroplasty procedures.

TIROBOT

TiRobot, developed by Tinavi Medical Technologies / Tianji, is a passive, 6-DOF arm, the first orthopaedic robot developed entirely in China [44]. Including the TiRobot, the Tinavi system comprises (Fig. 9) of a robotic arm, an optical tracking system, and a surgical planning and control station. The Tinavi system can be used for spinal surgery, as well as pelvic and limb surgeries [45]. TiRobot received China FDA approval in 2016, and reportedly has comparable intraoperative 3D navigation to similar surgical systems. Image data for procedures with TiNavi can be obtained through both intraoperative 3D fluoroscopy and C-arm scanning [44], [46].

Fig. 9. The Tinavi system is a passive robotic arm designed to assist with spinal and pelvic surgeries [117].

B. Robots for spinal surgery / neurosurgery

The use of robots combined with navigation has distinct benefits for surgeries around the brain and spine. Critical neurological and vascular structures around the spine are susceptible to damage from incorrectly positioned pedicle screws, with screws inserted via freehand methods sometimes resulting in poor accuracy [7]. Screw position accuracy can be improved through the use of intraoperative fluoroscopy, however this brings with it an elevated exposure to radiation for OR staff. A number of studies have shown robot assisted surgery is capable of improving the accuracy of screw insertion [47], [48], and separately, reducing the duration of fluoroscopy per screw [49], [50].

RENAISSANCE

Fig. 10. The Renaissance system is a passive patient mounted parallel robotic manipulator designed to assist in the placement of spinal pedicle screws [4].

The Mazor Renaissance (Fig. 10) is a soda-can sized robot, used for both neuro- (CE mark, 2011) and spinal surgery (FDA + CE mark, 2011) [4]. Renaissance mounts directly to the spine of the patient or the operating table, and integrates preoperative CT imaging with intraoperative fluoroscopy for guidance [7]. The preoperative plan generates virtual models of the surgical site, with the surgical team using the digital model to position and align the pedicle screws for the robot. This surgical plan is then executed by the robot under the supervision of the surgical team. Mazor Robotics was acquired by Medtronic in 2018 [51], and a new version of the Mazor system (Mazor X) was introduced in 2019 [52].

NEUROMATE

The first robot designed specifically for neurosurgery [5], Neuromate (Fig. 11.) is a passive 5-DOF robotic arm used for biopsy, deep brain stimulation, radiosurgery, neuroendoscopy, electroencephalography, and transcranial magnetic stimulation. Neuromate is considered a continuation of the first surgical robot by Kwoh *et al* [5], [10], and, as with the original experimental setup, the surgeon controls and guides the tool while the robot acts as a steady for the instruments. When used in conjunction with a stereotactic frame, Neuromate is capable of sub-millimetre accuracy, while the frameless configuration has a reported accuracy of 1.95mm [53]. The current third generation robot, along with its dedicated software Neuroinspire, received FDA approval in 2018 [54].

Fig. 11. The passive surgical robot Neuromate is designed for assistance during neurosurgical interventions [4].

ROSA – EXCELSIUS

ROSA (Robotized Stereotactic Assistant, Fig. 12) is a passive 6-DOF robotic arm used for neurosurgery and spinal surgery, improving placement accuracy of pedicle screws. The arm provide haptic feedback to the operator when approaching the extremities of the surgical plan, and uses a laser measurement system for less-invasive patient registration. ROSA does not require preoperative CT imaging, and can instead use either intraoperative CT imaging, or fluoroscopy [7]. The guidance system of ROSA dynamically accounts for the relative position of the patient and the robot, making motion during surgery inconsequential. ROSA received FDA approval for neurosurgery procedures in 2018, while the spinal system received FDA approval in 2016 [55].

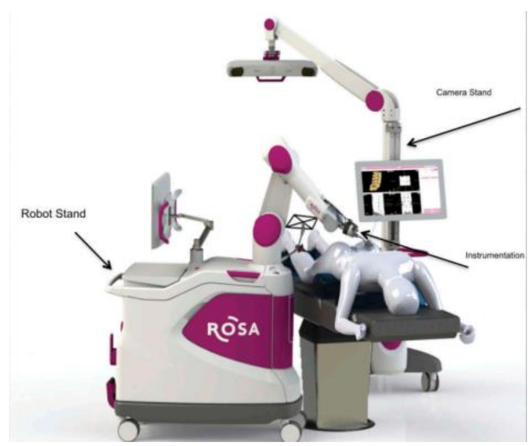

Fig. 12. The ROSA robotic surgical platform has been utilized for assistance during neurosurgical interventions on the head and spine [114].

C. Robots for other bone remodelling procedures

Outside the aforementioned fields of orthopaedics and neurosurgery, a number of more experimental approaches to bone remodelling have been tested with custom-built robots. Whilst these robots are not yet in clinical use, some aspects of these systems, such as tooling, process, or application, are particularly interesting.

AOT/CARLO

CARLO (cold ablation robot-guided laser osteotome, Fig. 13) is a miniaturized laser cutting system, developed by Swiss company Advanced Osteotomy Tools (AOT, Basel, Switzerland). CARLO is comprised of a laser cutting and visualisation system, connected to a lightweight medical-grade KUKA robot [115]. A low-power class I laser first indicates the planned ablation pathway, after which a class IV 2.94um Er:YAG laser is used to ablate the same pathway along the target bone [9]. A separate navigation system (Fusion track 500, ATRACSYS) is integral for the accuracy of the robot, with fiducial markers indicating the position of the patient and the tooling. Saline solution and medical air is used as a cooling spray during operation. CARLO has undergone preliminary testing in craniomaxillofacial (CMF) applications.

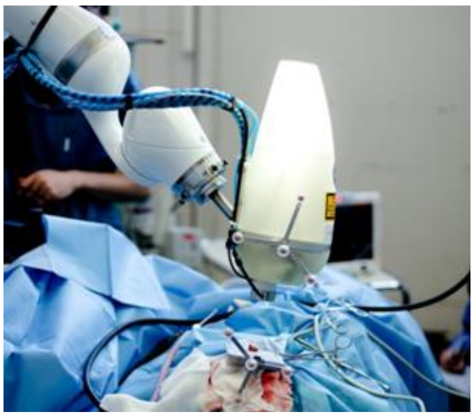

Fig. 13. The CARLO robotic system utilizes laser technology for ablation and cutting of bone [115].

MINIMALLY INVASIVE DIRECT COCHLEA IMPLANTATION SYSTEM

Acting on a proposed keyhole approach to cochlea access, a team of researchers in Bern, Switzerland, developed an active surgical robot to perform a minimally invasive cochlear implantation (Fig. 14). The system is comprised of an articulated robotic arm attached to the operating table, a navigation system, and software for planning + intraoperative monitoring. The robot is supervised and operated by a user with an on/off switch, with graphical user interface guiding the surgeon through the procedure, verifying the safety of the procedure at various defined stages [8]. The keyhole approach to accessing the cochlea was previously considered unattainable due to high precision anatomical constraints at the surgical site. In an area approximately 2.5mm x 2.5mm, a tunnel 1mm to 2mm in diameter is required to insert the cochlea electrode, leaving approximately 0.5mm between the tool and nearby nerves and critical soft tissue (including facial nerve, chorda tympani, ossicles, and a portion of the auditory ear canal).

The Minimally Invasive Direct Cochlea Implantation System (DCA) drills a tunnel through the mastoid, in accordance with a preoperative plan generated from CT images in conjunction with four implanted fiducial screws, with a geometric accuracy of 0.15mm +- 0.08mm at a depth of the cochlea. At stages throughout the drilling, the safety of the facial nerve is monitored through electromyography, while heat generation within the bone is mitigated through robotically controlled interval drilling. Other robotic systems for this application include custom head-mounted parallel robots [56], as well as re-purposed industrial manipulators [57] and miniature handheld systems for procedure sub-steps (cochleostomy) [58].

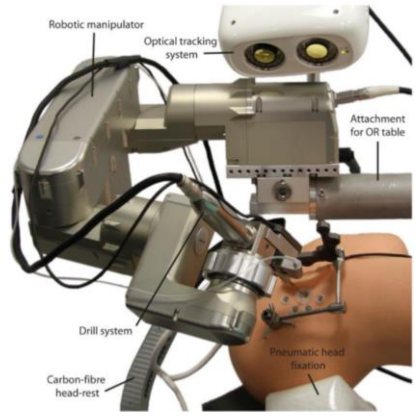

Fig. 14. A custom robotic system for minimally invasive cochlear implantation performs high accuracy drilling tasks autonomously [116].

The characteristics of each of the systems described above are summarized in Table I.

IV. TOOLS FOR REMODELLING BONE

Bone remodelling procedures are performed with only a limited set of common functions. For instance, a hole may be drilled in bone either to install a screw or allow the surgeon access to another organ. Similarly bone may be cut with a saw and removed in preparation for a replacement joint, or en-bloc removal of tumour tissue. The limited set of common functions for remodelling bone was previously shown in a study by Putzer *et al*, [59] in which 243 procedures from a bone procedure atlas (Campbell's operative orthopaedics) were analysed in an effort to consolidate a limited set of generic functions. 30 procedures were selected at random, from which 14 generic functions were identified; seven for planning, and seven for remodelling bone. These 14 functions were then applied as individual steps of a simulated surgery to theoretically complete each of the original 243 procedures. A significant result noted by the authors of the study was that the most important function – limiting the movements of active cutting tools and specifying the regions in which the tools should be switched off – is only available in robotic surgical systems. A secondary finding was that in the context of total instances of steps relating to removal of bone, drilling was used more than cutting or milling (55%, 33%, and 12% respectively). Proper execution of these bone remodelling functions depends on the method of cutting of each tool type, and the operator's ability to use the tool as intended. Putzer *et al* posited that remodelling functions involving cutting and milling were not as prevalent as those involving drilling due to the increased difficulty of accurately using saws and burrs without the assistance of a surgical robot. The tooling utilized in bone remodelling procedures will vary depending which of

TABLE I

CHARACTERISTICS OF CURRENT AND PREVIOUSLY AVAILABLE SURGICAL ROBOTIC SYSTEMS.

System	Surgical application	Autonomy	Planning	Patient registration	O.R. Footprint	DOF	Tooling
CASPAR	THA / TKA	Active	Intraop CT	Preop fiducials	Base + arm + navigation module	6	Burr / Drill
Acrobot	PKA / TKA	Semi-active	Intraop CT	Preop fiducials	Base + arm + navigation module	6	Burr / Drill
ROBODOC	THA / TKA	Active	Preop CT	Intraop fiducials	Base + arm	5	Mill
MAKO	THA / TKA / PKA	Semi-active	Preop CT	Intraop fiducials	Base + arm + navigation module	6	Burr, Saw, Reamer
iBlock	TKA	Passive	-	Fixed to bone	Bone mounted cutting guide [6]	2	Tool guide (saw)
NavioPFS	PKA / TKA	Semi-active	-	Optical	Base, Handheld tool	N/A	Burr / Drill
Tinavi	Spinal / Pelvic / Limb	Passive	Fluoroscopy	Optical	Base + arm + navigation module	6	Tool guide
Renaissance	Spine / Neuro	Passive	Preop CT, Fluoroscopy,	Fixed to bone	Bone / Bed mounted frame	5	Tool guide (drill)
ROSA	Spine / Neuro	Passive	Preop + intraop CT, Fluoroscopy	Preop fiducial	Base + arm + navigation module	6	Tool guide (drill)
Neuromate	Neuro	Passive	CT / MRI (preop)	Intraop fiducials / Stereotactic frame	Base + arm	5	Tool guide (drill)
AOT / Carlo	CMF	Semi-active	-	-	Base + arm	7	Laser
DCA	Cochleostomy	Active	CT	Fiducials	Table mounted arm	5	Burr / Drill

the above tasks are required. In addition to saws, drills, and burrs, more modern tools such as ultrasonics and ablative lasers can also be used in bone remodelling procedures. The following section will examine a selection of tools used to surgically remodel bone.

SAWS

A saw is a toothed blade that reciprocates or oscillates in line with the teeth of the blade, and will remove a slit of material approximately equal to the thickness of the blade (known as the kerf). The geometric features of a saw include the distance between each tooth, the height of each tooth, the angle of the cutting edge of each tooth, and the angle of the trailing edge of each tooth. Preferred materials for saws include stainless, high carbon, or high speed steels [1], and the teeth of the saw can be impregnated with diamond or carbide for improved cutting efficiency or longer tool life. The rate of material removal, as well as the depth of cut, is influenced by the pitch of the cutting teeth, with faster cuts made by coarse blades and narrower cuts made by fine blades. Saws can be linear and circular, however the cutting action is essentially identical. The theory of cutting can be explained by two dimensional cutting models, where an angled, pointed cutting tool strikes into a work piece and the perpendicular movement of the tool shears a smaller volume of material from the larger work piece. Saws are sometimes necessary for orthopaedic procedures due to anatomy, required cut geometry, or surgical access. The iBlock cutting guide is for use with a reciprocating saw, and the MAKO can also be fitted with an oscillating saw.

DRILLS/BURRS

Drilling is a fundamental machining operation, whereby a hole is cut in a material using a long rigid tool with a sharp cutting tip. Existing holes can be enlarged through 'boring', and improving the surface finish of an existing hole is referred to as 'reaming'. Drilling can occur at either low or high speeds. During low speed drilling, material is abraded at the cutting surface, while in high speed drilling the material at the cutting edge shears and separates from the host material [1]. The force acting in the direction of the hole axis is defined as thrust force, which is dependent on factors such as rotational speed, drill diameter and geometry, drill feed rate, as well as properties of the work-piece. Required drilling force decreases at greater drill speeds, and dissipation of drill power is a product of drill rotational velocity and torque. The measurement and correlation of these parameters relative to the thrust force is not altogether straightforward. The optimal rotational velocity for removing bone is unclear, however a study by Esen *et al* [60] found higher quality cuts could be achieved by keeping thrust forces constant throughout the drilling process. Furthermore, excessive thrust causes bone breakage and damage to the cutting tool, whilst inadequate thrust causes poor chip formation in cutting which in turn leads to higher temperatures at the cutting tool.

Milling is a similar process to drilling and is a versatile method of material removal, capable of performing cuts with a variety of paths and geometries. Milling can produce both flat and contoured surfaces, slots, steps, and irregular holes, although it is difficult to produce all of these outcomes with a single cutting tool. Milling tools (also known as mills or burrs) have multiple cutting edges spaced around a central axis, capable of producing a set number of chips of material per revolution [1]. The machining action and subsequent removal of material is a product of the rotation of the cutting tool, and the feed of the work piece.

As with sawing, the machining characteristics for cortical bone depend on the direction of the cutting tool, making for three possible directions of cut, relative to the orientation of osteons within the bone: perpendicular, parallel, and transverse [61], [62]. As surgical robots tend to follow or facilitate complicated tool paths and drills are restricted to producing precise holes set by the tool diameter, drills are less versatile than burrs.

LASER

With initial medical applications in ophthalmology and dentistry, lasers are now used in a range of medical fields, including orthopaedic surgery [63]. A laser is a device which emits spatially and temporally coherent electromagnetic radiation, resulting in a focused beam of light with uniform colour and luminosity [64]. This beam of light is able to increase the temperature of certain materials in its path, which, in the case of organic tissues, can result in pyrolysis, vaporization, and subsequent ablation of material [65]. By directing a laser beam's focus over a contiguous area or along a narrow pathway, sections of tissue can be precisely remodelled [66]. Due to their non-contact method of operation, laser cutting does not cause typical friction-related side-effects encountered by mechanical tooling [67]. Wallace *et al* assessed the thermal effects on bone from an Er:YAG laser with a thermocouple positioned 2mm from the ablation site. When combined with a constant spray of water, the maximum temperature increase was 6C after 20 seconds of lasing [68]. In comparison, Toksvig-Larsen *et al* assessed thermal effects of eight saw blades of varying design on cortical bone, using a thermocouple positioned 2mm from the cutting site. From the 219 tests performed, only three were below 47C, suggesting blade design has little influence on temperature changes at the cutting site [69]. Osteonecrosis has been shown to occur when bone temperature measures 47C for one minute, or 43C for one hour [70]–[74]. As such, there is significant motivation to maintain lower bone temperatures at a cutting site. As lasers do not require significant force to manoeuvre while ablating and affect only the area upon which they are focused, highly accurate and precise cuts can be performed more easily than with conventional tooling. A study by Baek *et al* [75] compared the workflow, ergonomics, safety, and accuracy of cutting operations between conventional drills, PZE tooling, and an Er:YAG laser. Two sets of four different osteotomy patterns were made in an in vitro setup, and in vivo porcine mandibles. For both in vitro and in vivo, one set of the patterns was performed with a robotically assisted Er:YAG laser prototype, the other set with drills and burrs. The time taken to perform each pattern was recorded, including the aseptic setup, navigation, patient registration, and the process of bone ablation. The authors noted that while the procedure had a steep learning curve, the time taken to perform the laser osteotomy decreased more rapidly than the conventional osteotomy. The accuracy of registration improved from the first surgery to the sixth surgery (1.5mm to 0.6mm root mean square error). Additionally there was no significant difference in time between the conventional osteotomy and the laser osteotomy, with a mean of 734 and 766 seconds respectively. Whilst these results suggest laser osteotomies are comparable in time and accuracy to osteotomies with conventional tooling, the procedures themselves have mostly been two-dimensional surface-level ablation, with less research having been performed on more complicated three-dimensional volumetric osteotomies. The CARLO system by AOT uses an ablative laser for precise craniomaxillofacial osteotomy procedures.

ULTRASONICS

Piezosurgery uses ultrasonic vibrations to assist with cutting, whilst providing an element of safety by minimizing damage to soft tissue, making it more suitable for surgeries around critical nerves and vessels [76], [77]. Piezosurgery was first used in a maxillofacial surgical operation in 2001 by Vercellotti *et al* [78], and is now a clinically effective method of osteotomy used in oral & maxillofacial procedures, neurosurgery, and orthopaedic surgery. Piezosurgery exploits the piezoelectric effect, whereby certain materials will physically deform when subjected to an electric current. With a controlled application of current, predictable oscillations of the material can be achieved, which can then be amplified and directed to a cutting tool [77]. If this vibrating cutting tip is applied to bone, the contacted area undergoes cavitation, and the region of tissue is ablated [79]. Histological evidence suggests improved bone regeneration post-surgery, compared to conventional techniques [80]. Surgery factors such as duration, intraoperative blood loss, and quality of cut during bimaxillary osteotomies were assessed by Bertossi *et al*, comparing the performance of conventional tooling (rotary burr and reciprocating saw) to piezo tooling. 110 study participants received mandibular osteotomy from one of the two tool types, with the duration of bone cutting taking between 7m23s to 10m22s for conventional tooling, and 3m31s to 5m2s for piezo tooling [81]. In contrast, despite performing similar bimaxillary osteotomies across two groups of patients, Spinelli *et al* found an overall increase in duration for piezosurgery by 35% ($p = 0.0018$) [82]. Moreover, a meta-analysis of piezosurgery bimaxillary osteotomy studies by Rana *et al* showed no difference in surgical duration between conventional and piezo tooling [76], suggesting that as Spinelli had far fewer participants than Bertossi (12 and 110 respectively), it is possible that greater familiarity with the procedure was developed with the larger sample size, and that repetition of the process lead to improved skills with the piezo tooling and more opportunities to implement these improved skills and decrease operating time. No surgical robots are currently known to utilize ultrasonic or piezosurgery tooling for bone remodelling.

WIRE SAW

Wire saws, also known as gigli or threadwire saws, are flexible braids of metal able to be wrapped around bone, allowing cuts from behind or underneath the tissue. Originally devised to simplify a lateralized pubiotomy [83], wire saws are guided behind the region of bone to be excised, then pulled back and forth from alternate ends until the saw passes through the bone. Although wire saws are used by industrial robots for manufacturing, there are no examples of wire saws used by a robot for surgical purposes.

V. Discussion

A. *Benefits of robots*

Studies on surgical robots typically focus on direct improvements from robots during surgery, such as accuracy of robot assisted bone resections compared to manual, or position and alignment of pedicle screws. Retrospective studies of indirect benefits of robotic surgery include reduced length of stay, and long term data comparison of procedures.

Tool accuracy

One significant study on the advantages of surgical robots assessed the ability of a surgeon to perform a freehand cut with an oscillating saw, compared to navigated cutting, and an active robot. Cartiaux *et al* [84] assessed the quality of freehand cuts and navigated cuts into a rectangular bone analogue from six trained operators (12 cuts each operator for both freehand and navigated), compared to 12 cuts performed by a Viper s650 equipped with an oscillating saw. A single angled incision was made in each rectangular block. No significant difference was observed between individual operators, nor were there any obvious effects of a learning curve with the cuts. The study determined dramatic improvements in the quality of cuts performed by the robot, and significant improvements in accuracy of cut flatness and location when performed with navigation, compared to the freehand process. A similar study by Khan *et al* [39] assessed the deviation from a planned multiplanar osteotomy, comparing freehand sawing with robotic assisted sawing using a MAKO robot. A single resection plan was performed on 12 sawbones specimens, six freehand and six with robotic assistance. After resection, virtual models of the resected sawbones were compared against the original osteotomy plan, finding a mean improvement of 7.9° pitch, 4.6° roll, and 7.8mm of maximum linear deviation, compared to freehand resection methods. These two studies in particular are concise examples of the improvement in accuracy provided by robots; Cartiaux *et al* demonstrated the improvement provided by robots for angle and position for straight cuts in rectangular bone blocks, while Khan *et al* demonstrated the improvement in relative and absolute alignment and position of multiple cuts in bone analogues.

State monitoring

Surgeons are heavily reliant on both vision and touch to effectively perform procedures. Surgeons can palpate tissue when vision is obstructed, however active and semi-active surgical robots diminish a surgeon's touch sensation through their autonomous actions and mechanical systems. A variety of sensor types can be utilized by robotic systems to determine their current position and state. Internal sensors such as encoders allow a robot know its position and velocity, vision is also commonly used to locate tools relative to the patient. Force and torque (FT) data has also be applied to ascertain information about the robot's environment or state of a task. In the context of surgical robotics, Brett *et al* [85] used FT data in cochleostomy surgery to detect the moment a burr breaks through bone and stop the tool before penetrating a membrane. Kanzazides *et al* [86] measured FT data to control the spindle speed of a burr, increasing the speed when forces were lower and decreasing the speed when forces were higher. A control scheme by Sugita *et al* [87] varied the tool spindle speed and feed rate based on FT data and temperature. Al-Abdullah *et al* [88] proposed an artificial neural network-based method to discriminate between different bone densities during robotic bone milling, in which the current cutting force is compared with a set of estimations for different bone densities under the same cutting conditions. Dai *et al* [89] proposed an analytical method for modelling bone dynamics as tissue is removed. The vibration of the bone during cutting operations was measured using a non-contact laser, with particular attention given to harmonic components related to the tool spindle frequency. Williamson *et al* [90] utilized FT to detect the position of a tool during blind drilling of the skull; the algorithm utilized the variable density of the bone and detected force to provide an independent position measurement. FT data is invaluable for state monitoring in surgical robots, enabling comparisons between the expected state parameters from the surgical plan and the parameters of the current state, as well as improving the safety of surgical robots through collision and state detection.

Safety

Surgical robots can provide additional intraoperative safety measures which would otherwise be unavailable in a procedure executed freehand. For example, the keyhole approach to cochlea access, as performed by Caversaccio *et al* [8] required high precision drilling to avoid critical structures, which was monitored by a number of intuitive safety features. Whilst the robot functions without operator instruction, the actions taken by the robot are still performed under the supervision of a user with an on/off hand-switch, minimizing the likelihood of erroneous robotic actions during the procedure, or at the very least, allowing the operator to interrupt a robotic process should the task execution deviate from what was expected. A more elaborate safety measure assesses the cutting tool's proximity to the facial nerve, by performing electromyography through the drill; if the drill is too close to the facial nerve, the connected musculature responds to the EMG from the drill, indicating potential risk to the nerve if the cutting trajectory is not changed. Additionally, accumulation of heat in the drill and tissue is minimized by allowing the robot to perform efficient interval drilling, minimizing the likelihood of excessive force applied to the cutting tip without extending the duration of the drilling process. Both the prevention of nerve damage through drill-bit EMG and the efficient interval drilling would be beyond the control of a human operator alone.

In a similar application, a handheld robotic system utilized for access to the inner ear (drilling of a cochleostomy) utilized force and torque measurements to detect the imminent breakthrough of the tool into the cochlea, protecting the delicate inner structures from burr penetration, as well as debris [58]. Similar concepts utilizing force and torque to protect soft tissue surrounding bone have been described in orthopaedic and spinal applications [88], [91], [92]. The use of tissue impedance during the robotic performance of machining tasks has also been investigated [93], with similar concepts demonstrated using handheld tools in spinal [94] and dental procedures [95], [96]. Robotics also has the potential to improve procedure safety by combining multiple sensor types, imaging modalities and evaluation approaches into a comprehensive robotic "safety net". This concept has been previously demonstrated for minimally invasive cochlear implantation, but has the potential to be utilized in a variety of fields, particularly when the robotic system is required to work in close proximity to critical structures such as nerves or vessels [97].

One final point of consideration with respect to robotic safety is the robotic systems themselves. Previous generations of surgical robots have been largely based on industrial robots. These systems tend to be large, powerful and capable of reaching speeds and applying forces well above those required in surgery, potentially causing injury to the surgeon, surgical team or patient. In an industrial environment, these systems are typically isolated from human co-workers for this reason. The rise of so called "co-bots", or cooperative robots, in an industrial setting [98], as well as the design and uptake of new systems specifically optimized for surgery, including factors such as fail safe design methods will lead to further improvements in robotic and procedure safety [99], [100].

Clinical and Patient Outcomes

The largest body of literature investigating the potential advantages of robotics covers the improvements in specific patient or clinical outcomes related to the specific procedure being performed. For example, a systematic review and meta-analysis from 2018 by Gao *et al* [101], primarily assessing the Mazor spinal robot, concluded that, compared to freehand methods, robot-assisted pedicle screw surgeries had equivalent implantation accuracy, a reduction in radiation exposure, fewer proximal facet joint violations, but a longer overall duration of surgery. In an orthopaedic context, a number of studies [29], [31]–[33] have shown that postoperative pain, biomechanics, implant function and implant longevity can all be improved by returning the leg to optimal alignment, i.e. restoring the mechanical axis of the leg to neutral (defined as within 3 degrees of a straight line between the centre of the hip, the knee, and ankle). Whilst surgical robots can assist with this alignment, optimal outcomes are not solely dependent on accuracy of cuts within bone. A cadaveric study by Crottet *et al* [29] found complications such as implant instability and loosening, as well as malrotation and misalignment were a result of surgical techniques which inadequately address soft tissue balancing, with Pang *et al* [34] achieving improved restoration of limb alignment using Depuy Orthopaedic Inc. / Brainlab gap balancing software. Finally, recent studies of the ROSA system have shown that robot-assisted neurosurgery is an efficient and reasonable alternative to frame-based techniques, with a reduction in operative time, improved safety and feasibility of minimally invasive approaches, and no increase in morbidity or mortality [102], [103].

Future research

Among the current issues with surgical robots is that the surgeon has limited knowledge of what the robot's next move will be, or whether the robot's next action will be the correct action. While preoperative planning allows surgeons and clinicians to have a better understanding of what to expect during surgery, there is scant information available *during* surgery to keep clinicians abreast of the robots upcoming actions. Complicating matters is the time involved with the preoperative planning phase of a surgery. As robotic surgical procedures become more commonplace, the time spent planning would likely increase, potentially trading intraoperative man-hours for preoperative man-hours. Furthermore the advent of additive manufacturing and patient-specific implants would require extra attention in planning due to the unique nature of each case. This unique surgical plan would require precise positioning of cutting planes and tool paths, but to the authors knowledge, no system or software exists which quantifies critical clinical factors affected by a surgical plan or optimizes a plan based on these factors. For example, a cutting plane's position and orientation is set by the surgeon according to their experience and medical guidelines, however this placement is not necessarily the optimal solution.

The 2004 report "OR 2020: The Operating Room of the Future" [104] presents the results of a collaborative workshop set up to identify "the clinical and technical requirements for integrating advanced computer-assisted and robotic technologies into next generation operating rooms and interventional suites". With regard to surgical robotics, the document reports four main potential areas of research in the field, which are still of significance at time of writing: Means for improving cooperation and communication between robotic systems and humans to ensure safety and broader applicability of technology; Development of semi-automatic or shared autonomy systems incorporating robotic technologies and monitoring by surgeons; Built-in safety checks and mechanisms for process validation, and; means for mining massive streams of surgical data. Research into these areas remains on-going, although a number of novel solutions are slowly being developed.

In addition to these identified challenges, current directions of surgical robot research include integration of augmented / virtual reality systems for improved visualisation of surgical plan, optimization of path planning through artificial intelligence (AI) and machine learning, and elaborate path planning and minimising surgical access requirements.

Augmented reality (AR) and virtual reality (VR) can provide additional detail to surgeons in both the planning and operative stages of a procedure. Using VR and AR, surgeons, clinicians and technicians are able to collaborate in virtual three-dimensional space, planning alternative surgical approaches, or identifying critical anatomical features which may be unclear in standard two-dimensional imaging. A study by Cho *et al* [105] evaluated the accuracy of an augmented reality (AR) based navigation system through simulated resection of porcine bone tumours. The surgical margin was assessed with respect to the preoperative plan, finding a mean error of 1.71mm across 164 resections in 82 porcine femurs when an AR system was used. By comparison, conventional resection techniques produced a mean error of 2.64mm across 82 resections in 41 femurs. Integrating AR and VR systems with surgical robotics could allow surgeons to see the expected actions of the robot, such that the surgeon can see the next move of the robot before a process is performed. Allowing the surgeon to 'see' the robot's next move in advance would increase the safety of surgical robots, as the robot's action would only be permitted to occur if the next move was correct.

Cutting parameters controlled by a surgical robot can include depth of cut, tool spindle speed, and feed rate. The optimal combination of these parameters allow for low cutting temperatures, forces, and duration of cut. Determining the optimal values for these parameters is difficult due to the variation in bone density and composition. Kianmajd and Soshi [106] introduced a methodology of determining the optimal tool type and accompanying tool path for safe and rapid cutting of bone. Genetic algorithms were used to optimize multiple objectives simultaneously, such as cutting forces, temperature, and duration. Iterative simulation of different input parameters identified a set of values with a highest material removal rate, which did not exceed limits for cutting forces or torques. Tool path optimization algorithms can eliminate unsafe approaches, and reduce duration of surgery. Future AI and machine learning systems may be able to calculate tool paths from bone density image data or statistical information, identifying cutting parameters and tool paths which exert the least force on the bone.

Joint arthroplasty and other bone remodelling procedures often require extensive surgical access. Skin, muscle, and other soft tissue must be retracted clear of the intended tool path to ensure unimpeded cutting of bone. Reducing the surgical opening improves postoperative results for knee arthroplasties, however this reduction causes problems with tool posture and path generation. The reduced surgical opening restricts the range in which the cutting tool can enter the joint, and the tool must have a deeper reach to not collide with the soft tissue. Studies by Sugita *et al* examine the optimal initial position of the cutting tool to minimize contact with the surrounding tissue [107], modelling soft tissues as an interference area [108], and geometrically optimizing the tool path for minimizing collisions with a tool path generated from this model [109]. Collectively these articles propose a tool path generation method to minimise the necessary soft tissue incision then calculate the optimal tool path to avoid collision with the soft tissue. The possible interference with the soft tissue was minimized by using fewer posture changes for the bone cutting robot. For minimally invasive surgery, the authors state the issue of tool collision is a geometric problem of cutting a large area through a small opening. State-of-the-art cutting tools combined with additive manufacturing may lead to patient-specific tools cutting bone through keyhole surgical access, ablating the bone in-situ and replacing the tissue with a self-assembling prosthesis.

Combining just a small selection of these research streams into an operating theatre of the future could see surgeons receive detailed patient pathology through VR, with an AI system calculating the optimal cutting path to minimize bone loss, and the accompanying tool and reconstructive implant additively manufactured while the patient is prepared for surgery.

VI. Conclusion

Surgical robots are a relatively new option for surgeons, and their future in bone remodelling is promising. Though the lack of long-term follow-up studies limits what advantages can be stated, the current state of the field suggests largely positive results. Improvements in accuracy and cutting precision has enabled better fitting implants and prostheses, with less pain for patients and fewer revision surgeries. Obvious drawbacks of surgical robots include the cost of developing new systems, incorporating systems into an operating theatre, and ongoing maintenance expenses. As with any new system, the learning curve associated with surgical robots means users take time to become proficient with the equipment, and procedures performed early in a robot's existence may be more prone to error than those performed with well-established systems. However, the benefits demonstrated to patients thus far justify both the expenses and the additional learning period, as shorter hospital stays, fewer revisions, and reduced morbidity are all not only significant to the individual, but also the medical industry as a whole.

Since their first application to surgery, technological advances in robotics have seen increased application in surgical procedures, as well as assistance with both preoperative and intraoperative aspects of surgery. Improvements in postoperative biomechanics and reductions in revision surgery can be traced back to improvements in cutting accuracy provided by surgical robots, and the systems required to plan and precisely execute a given procedure. The safety of robotic surgery has been demonstrated in orthopaedics, however their relatively recent existence means long-term benefits or complications have not yet been identified. Studies have shown the improvements achieved by robots in relation to factors such as limb alignment, intraoperative blood loss, and decreases in operative time; however the role of robots in bone remodelling is still emerging.

The future of surgical robotics looks bright: additional systems are undergoing clinical evaluation each year, while the surgical robotics market is expected to exceed USD$91.5 billion by 2025 [110]. There is a trend towards increased automation in medicine, particularly with recent advances in artificial intelligence and machine learning for image analysis and automated planning. Surgical robots are set to take their place at the forefront of this push. The use of robotics will potentially allow the performance of more elaborate tool paths using specialized cutting tools, with the potential for robots to perform procedures currently impossible for a surgeon to complete manually. Improvements in access to additive manufacturing/3D printing will allow for the creation of highly patient-specific implants; the accurate excision of tissue and placement of these devices is one area ideally suited to robotic machining, with these two technologies complementing each other. Machine learning algorithms and artificial intelligence have applications in generating patient-specific tool paths, and minimizing the time spent in preoperative planning. Finally, as robots become more common in the OR, the integration of these devices into existing infrastructure and workflows will continue to improve, while new workflows will develop. The utilization of sensor data intra-operatively, in combination with imaging and personalized patient information may lead to improved system safety and potentially improved clinical outcomes.

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