Joint replacement in the 21st century: how modern imaging and surgical technology combine

By D.G. Houlihan-Burne & Dr. R Hughes

INTRODUCTION

Hip and knee total joint arthroplasy (TJA) are some of the most commonly performed surgical procedures throughout the world. Hip replacements have been performed in the UK since the 1960s and knee replacement since the 1970s. In 2017 alone, more than 91,000 hip and over 102,000 knee replacements were performed in the United Kingdom [1].

These operations have revolutionised the management of painful and often crippling osteoarthritis and remain highly cost-effective solutions from a societal perspective [2]. The demand for TJA continues to rise year-on-year and, with an ageing population the increasing economic burden of this surgery are not insignificant. Recent modelling has predicted an exponential growth of 66% in the numbers of TJA procedures over the next 20 years [3]. It is therefore more important than ever that surgeons perform highly successful, long-lasting joint replacements, ensuring that these replacements need to be performed only once during the patient's life, so reducing the need for complex and expensive revision surgery [4].

The prostheses used for TJA, and the techniques to implant them, have continued to improve over the decades. However the need for even more improvements in outcomes is being been driven by evidence from the U.K. National Joint Registry whose data show significant variability in outcomes between individual surgeons, hospitals and different prosthetic implants. Sixty years after the inception of TJA we continue in 2019 to strive for the '*forgotten joint*', when a patient is actually unaware of ever having had a TJA. Current imaging and surgical technologies are focussed towards achieving this goal.

The Authors

D G Houlihan-Burne,
Consultant knee surgeon,
Fortius Clinic, London, UK.

Dr. R Hughes,
Consultant Radiologist,
Fortius Clinic, London, UK.

Corresponding author:
D Houlihan-Burne
email: david.houlihan-burne@fortiusclinic.com

CURRENT CHALLENGES WITH TJA

Patient dissatisfaction rates following total knee replacement have in the past been reported to be as high as 50% [5] with current accepted figures running between 0-20% [6]. The challenges of TJA include adressing such patient dissatisfaction, as well as avoiding early failure with its subsequent requirement for revision surgery. Causes of early failure of TJA include infection, excessive wear of polyethylene bearings, and loosening of the bone implant interface [7]. Apart from infection, these failures are a consequence of mechanical overload due to mal-alignment or overload related to patient activities. The causes of patient dissatisfaction, however, have always been difficult to diagnose and are considered multifactorial. There are recognised patient-related factors associated with dissatisfaction and poor outcomes (co-morbidity, diabetes, obesity, females from low income households, ruminators/depressive effect) but there are also implant factors (mal-alignment, mal-rotation, poor soft tissue balance).

The implant factors are thought to be avoidable, and can be attributed to surgical error and mal-alignment of the implanted components. Not only do these cause early failure, but it has also been suggested that they are a direct cause of dissatisfaction and pain following total knee arthroplasty (TKA).

Over the last few decades, strategies to reduce mal-alignment and improve survivorship and clinical outcomes have been addressed using implant kinematic design, navigation systems, patient-matched implants ('bespoke knees') and patient-matched cutting guides. All of these systems relied on various modalities of pre-operative imaging, predominantly using CT or MRI scans. Despite early enthusiasm, the results failed to show that improving alignment on its own was the solution to improved outcomes. Although there is no doubt that alignment plays a role, nevertheless the art of soft tissue balance of the knee, through its whole range of motion, is also important, (perhaps even more so than mal-alignment) in assuring patient satisfaction and succesful long-term functioning.

ROBOTIC-ARM ASSISTED TOTAL JOINT ARTHROPLASTY

The first documented use of robot-assisted surgery occured in 1985 when a robot was used in neurosurgical biopsy surgery [8]. It quickly became apparent that robotic technology allowed for greater precision when used

Figure 1. The MAKO Robot system from the Stryker Corporation.

for minimally invasive surgery such as laparoscopies. The first laparoscopic procedure involving a robotic system was carried out in 1987 and in 1990 the AESOP system became the first system system to be approved by the FDA. Ten years later, in 2000, the da Vinci Surgery System became the first FDA-approved robotic system for general laparoscopic surgery. Orthopaedic surgery was not far behind when in 1986 the Robodoc was developed for total hip arthroplasy, first used on humans in 1992, however with variable success. The Mako surgical corporation developed the Rio robot in 2004 and this was further developed with clinical trials beginning in 2006. Mako was acquired by Stryker Ltd in 2010 for $1.65 billion and the Mako/Stryker system [Figure 1] remains the most commonly used robotic system for TJA, having been used in over 100,000 procedures to date. The system, technology and applications have been described in more than 50 peer-reviewed clinical publications, with in addition more than 350 scientific abstracts being presented at peer-reviewed scientific conferences.

The MAKO robotic arm assisted TJA [Figure 1] relies on preoperative imaging to create a 3D reconstruction of the patient's native knee anatomy. A patient-specific model is created from the scans using generic software [Figure 2]. This is used to calculate a haptic window to plan bone resection, to allow the selection of implant size and its positioning for the desired bone coverage, and consequently, limb alignment. An interactive robotic-arm with visual, audio and tactile resistive feedback then guides bone resection within this predefined haptic window. Intraoperatively the surgeon is able to dynamically reference and assess the balance of the joint, the joint stability, the range of movement and limb alignment. In this way the surgeon now has the ability to perform on-table corrections and modifications in order to optimise the position of the implants and soft tissue balance of the knee and subsequently reduce mal-alignment, soft tissue imbalance and increase patient satisfaction and longevity of the knee, all in the quest for 'the forgotten joint'.

IMAGING AND ROBOTIC KNEE REPLACEMENT

Advances in Computer Tomography (CT) scanning and the development of software to map the patient's knee and plan surgery have revolutionised TJA. The combination of advanced imaging techniques with accurate and reproducible robotic systems, has thus provided surgeons with the ability to accurately pre-plan surgery. Pre-operatively we can decide on bone cut angles and depths, overall limb and implant alignment, and execute these decisions on our patients with an accuracy that was previously impossible. The patients are imaged pre-operatively with plain radiographs of the hip or knee and full length leg CT scans.

CT scanning has been a constantly evolving technology since its early clinical use in the 1970s. With the widespread introduction of spiral multislice scanners in the last 15-20 years and rapid advances in computer hardware, software and display technology, multiplanar and volume-rendered reconstructed data have been widely adopted in various clinical fields [9]. Some of the first clinical applications of volume rendering were in skeletal imaging with CT reconstructed data being used to plan orthopaedic implants as far back the mid-1980s [10]. Since then, CT has become an important part of the assessment of complex and custom-made prostheses as the technology allows for detailed assessment of anatomy, torsion and bone stock around various orthopaedic implants. CT has become important for

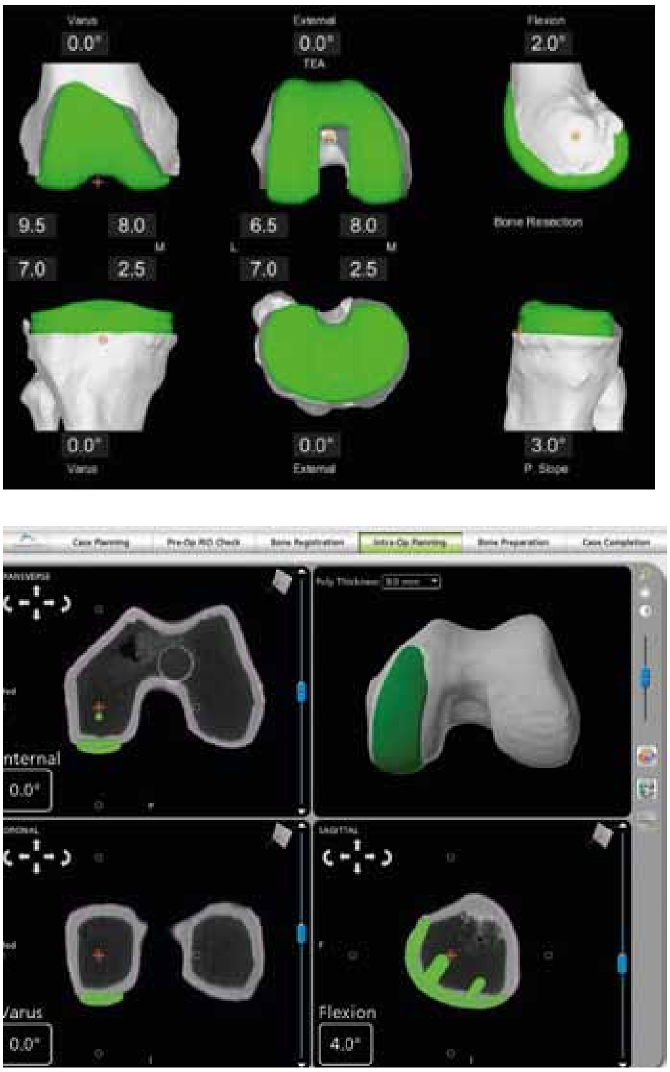

Figure 2. Computer generated images from CT scans of patient's knee to plan surgery pre-operatively.

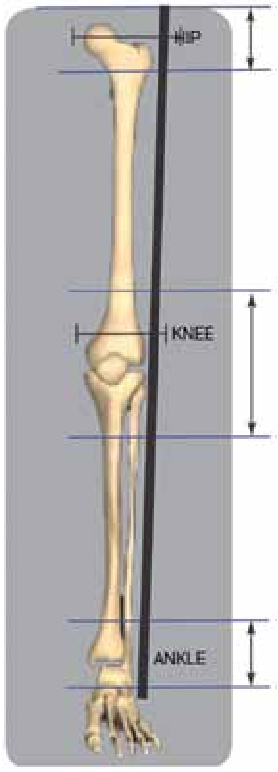

Figure 3. The pre-op CT slices at hip, knee and ankle

surgeons to visualise deformities and in designing custom implants [11].

MRI volume scanning has also been utilized in prosthetic planning and patient specific instrumentation (PSI) has been planned using both MRI- and CT-based protocols [12]. Both modalities show good correlation with mechanical total knee replacement (TKR) parameters. Additional studies will further assess the optimal modality and protocols.

We use CT to generate a 3D model in the MAKO system. In this, the patient is positioned supine and feet-first prior to volume acquisition through the hips, knees and ankles [Figure 3]. The scan can be acquired at any time within 8 weeks prior to the surgery. Radiation dose is on average approximately 4-5 mSv, but with the increasing development pace of CT systems and related technology, this is likely to decrease in the future.

The Stryker/MAKO system has a large database (Stryker Orthopaedic Modelling and Analytics, SOMA) containing over 15,000 prosthetic knee cases which can be used to check design against a number of demographic variables. Analysis of the designs using this database and fit-testing are key parts of the planning and design process.

In robotic TKR, the volume analysis provided by CT is used to generate a 3D model — this is key to the process as this is the foundation of the robotic procedure. The MAKO system uploads the CT data and uses it to generate a patient specific model for 3D printing. The in-house 3D printing technology allows for highly accurate modelling without the linear constraints of traditional manufacturing process.

Of course, the 3D model so generated must then be interpreted by the surgeon and used to plan the surgery.

RESULTS AND OUTCOMES

The marriage between modern imaging and technological surgical advances is new and evolving. Early results using imaging and surgical techniques to optimise patient outcomes are very encouraging. In 2102 a cadaver-based study reported results generated by surgeons who were highly experienced in conventional knee replacement surgery, and who then performed robotic knee replacement surgery. The results showed significantly better precision in the sagittal and coronal planes of the implant with the robotic implants and demonstrated improved accuracy in femoral rotational alignment compared to conventional methodology [13] .

Many clinical studies are now being published which replicate these results, showing that robot-assisted TJA has clearly the ability to provide super-accurate implant positioning [14]. The radiological advances of robotic arm joint replacement surgery are now being shown to have clinical relevance, with recent studies reporting several advantages compared to traditional TJA. These advantages include lower postoperative pain and analgesic requirements, reduced time in hospital, and quicker functional recovery [15,16]. Time will tell whether the longer term benefits are also realised, but there is currently much excitement in the surgical community that these new techniques will continue to revolutionise TJA, so paving the way for future, more complex interactions between imaging and surgery for the benefit of our patients. These developments hold out the promise that we will soon be able to achieve on a regular basis the ultimate goal of the "*forgotten joint*".

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