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Artificial intelligence and surgical innovation: lower limb arthroplasty

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Abstract

The number of patients requiring hip and knee arthroplasty continues to rise each year. Patients are living longer and expecting to remain active into later life following joint replacement. Developments in computer-assisted surgery and robotic technology may optimise surgical outcomes and patient satisfaction following lower limb arthroplasty. The use of artificial intelligence in healthcare is rapidly growing and has gained momentum in lower limb arthroplasty. This article reviews the use of artificial intelligence and surgical innovation in lower limb arthroplasty, with a particular focus on robotic-assisted surgery in total knee arthroplasty.

Key words: Robotic-assisted surgery; Artificial intelligence; Total hip arthroplasty; Total knee arthroplasty; Computer navigation

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Introduction

The term ‘artificial intelligence’ refers to the theory, development and implementation of computer systems to perform tasks that are commonly undertaken by humans (Jones et al, 2018). Over the last 70 years, artificial intelligence has grown rapidly with the development of computer models and algorithms to replicate human intelligence and perform specific tasks within various industries. Artificial intelligence provides accurate, objective, real-time data to optimise efficiency, increase accuracy, reduce wastage and minimise the risk of a system error, which enables high levels of performance and productivity that were not possible using humans alone (Jones et al, 2018; Panchmatia et al, 2018). These computer systems are now interwoven into the workforce of industries including the aviation, automobile, and healthcare industries.

Artificial intelligence has led to improvements in safety and cost-effectiveness in the aviation industry that would never have been possible with manually-controlled aircrafts of the past. Aircraft autopilot systems use real-time data related to wind speed, humidity, barometric pressure, altitude, weight distribution, turbulence, moments of inertia and an infinite number of electronic and system setting combinations to determine how to follow a flight path that is changing in real time (Bohn, 2005; Haddad, 2017). The flight path can then be altered to optimise fuel efficiency and passenger comfort. Computer technology is also routinely used to train pilots to ensure they have reached full proficiency before undertaking passenger flights.

Artificial intelligence has helped to increase production in the automobile industry by shifting from traditional assembly-line manufacturing to a streamlined computer-controlled manufacturing process (Pettigrew et al, 2018). The computer links a variety of processes, such as design, distribution, inventory control and analysis functions. Within vehicles, artificial intelligence has been used to develop inbuilt parking sensors, night vision with pedestrian detection, automatic high-beam control, parental control, satellite navigation, parking cameras, inbuilt electronic fuel sensors, temperature and tyre pressure sensors, keyless entry, smartphone integration, heated seats, adaptive cruise control and self-parking cars (Pettigrew et al, 2018).

Within healthcare, most medical professionals now routinely use artificial intelligence to access patient notes, review blood tests, assess patient images and electronically log patient reports and progress. Some specialities are well established with the use of artificial intelligence for routine patient care. These include anaesthesia, intensive care medicine, interventional radiology and internal medicine, which rely on computer technology for detailed monitoring and fine-tuning treatment. Other specialities, such as general surgery,

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gynaecology and orthopaedics, have seen increased use of computer technology to improve clinical care and facilitate earlier return to a premorbid level of function (Loulmet et al, 1999; Lehr et al, 2011; Haugen et al, 2013; Linsky and Wei, 2017).

Anaesthetists routinely use intraoperative artificial intelligence to measure, record, analyse and fine tune the administration of medication. The anaesthetic monitor displays a continuous electrocardiogram waveform, blood oxygen saturation, heart rate, blood pressure (systolic, diastolic, mean), body temperature and capnogram waveform through the breathing cycle with digital values for inspiration and expiration. If a central venous or arterial catheter is inserted, the monitor presents a continuous waveform with readings of systolic, diastolic and mean pressure values. If a neuromuscular monitor is being used, it displays the values of the muscle strength in response to an electrical stimulus applied to the nerve supplying that muscle (Haugen et al, 2013). This helps the anaesthetist to decide when to give more muscle relaxant and when to reverse the relaxant, and provides the concentrations of the volatile agent in each breath at the beginning of inspiration and the end of expiration. Computer technology in anaesthesia has now become an integral part of patient safety and 'anaesthetic machine check' has been implemented into the World Health Organization surgical checklist to be completed before the induction of anaesthesia (Haugen et al, 2013).

More recently, computer technology and robotic-guided surgery have been implemented into orthopaedics, and these provide a platform for developing the use of artificial intelligence in lower limb arthroplasty.

Lower limb arthroplasty: computer navigation and robotic-assisted surgery

In arthroplasty surgery, computer navigation and robotic-assisted surgery have been used as adjuncts to reduce human errors in bone resection and improve the accuracy of implant positioning. Computer navigation involves the use of computer systems that provide live on-screen information on patient anatomy and knee kinematics during surgery. This osseous anatomical map of the patient's knee joint may be obtained using preoperative computed tomography scans (image-based navigation) or intraoperative mapping of bony anatomical landmarks on a generic model of the knee joint (non-image-based navigation). Computer navigation provides patient-specific anatomical data with recommendations for bone resection and optimal implant positioning. However, the computer system does not actively control or restrain the motor function of the operating surgeon. Robotic-assisted surgery uses computer software to convert anatomical information into a virtual patient-specific three-dimensional reconstruction of the knee joint, which the operating surgeon uses to calculate optimal bone resection and implant positioning. An intraoperative robotic device helps to execute this preoperative patient-specific plan with a high level of accuracy.

Robotic-arm Interactive Orthopaedic System (RIO; Stryker Mako, Kalamazoo, MI, USA) is the only robotic system to offer robotic technology for hip, total knee and unicompartmental knee arthroplasty. Preoperative computed tomography scans are used to create computer-aided design models for preoperative planning and a robotic arm with visual, tactile and audio feedback helps to execute the planned bone resections within the confines of the stereotactic boundaries. Food and Drug Administration approval was obtained in 2015 and there are now over 1000 active surgeon users of Mako worldwide. So far, 83 000 hip and knee Mako procedures have been completed, and Mako accounts for 20% of the market share in unicompartmental knee arthroplasty over the last 8 years (https://www.stryker.com/us/en/portfolios/orthopaedics/joint-replacement/mako-robotic-arm-assisted-surgery.html).

Omnibiotic (OMNIlife Science Inc., East Taunton, MA) is a robotic device that uses patented intraoperative Bone Morphin technology to create a three-dimensional model of the osseous anatomy using plain radiographs. This avoids the need for additional costs and radiation exposure associated with preoperative computed tomography from image-based robotic systems. A robotic arm is then used to execute the planned bone resection and guide implant positioning. More recently, the OMNIbiotics alignment system has been combined with the BalanceBot Ligament Balancer (OMNIlife Science Inc., East Taunton, MA), which uses an intraoperative robotic device to balance the soft tissues. Together, these robotic technologies may help surgeons place implants anatomically while minimising the need for soft tissue release. Over 170 000 Omnibiotic total knee arthroplasty procedures have been performed since 2010 (https://www.omnils.com/patients/omnibotic_surgery/).

The Navio Surgical System (Smith and Nephew, Andover, MA) robotic device uses intraoperative bone mapping to create a virtual three-dimensional model of the patient's native knee anatomy. This eliminates the need for preoperative computed tomography and so reduces costs and radiation exposure, although this limits the capabilities of preoperative planning. Handheld apparatus is used to execute the planned bone resection. It offers three different knee options (including the Journey II XR bicruciate knee system) and its cost is approximately half that of the Mako robotic device. Food and Drug Administration approval was obtained in 2012 under the previous developer (Blue Belt Technologies, Plymouth, MN, USA) (www.smith-nephew.com/professional/microsites/navio/).

Rosa robot (Zimmer Biomet, Warsaw, IN, USA) is a robotic device that can handle brain, spine and knee applications. The Rosa robotics knee features imageless capability, although plain radiographs may be used to aid surgical planning. This system can implant different sorts of Zimmer Biomet knees (for example Persona and Vanguard), and does not require a robotic product specialist, which helps to reduce costs. Food and Drug Administration approval was obtained in 2019 (https://www.zimmerbiomet.com/medical-professionals/knee/product/rosa-knee-system.html).

These systems have all generated great interest but are very different, so each must be evaluated separately. It is important to note that the evidence cannot be used to cross reference from one system to another.

Developments in knee arthroplasty

It is reported that up to 20% of patients describe residual pain, disability and limited quality of life after an otherwise uncomplicated total knee arthroplasty (Noble et al, 2006; Milner, 2009; Bourne et al, 2010). Innovative technology, such as computer navigation and robotic-assisted surgery, was initially designed to improve the accuracy and precision of the bone cuts. The premise of these technologies was that improvements in the accuracy of component positioning and limb alignment would translate to improved patient satisfaction, better functional outcomes and longer implant survivorship (Haddad and Horriat, 2019).

After an initial surge in popularity, the use of computer-assisted navigation in total knee arthroplasty has decreased in recent times. Multiple studies have reported that computer-assisted navigation produces improved alignment compared to conventional jig-based techniques (Spencer et al, 2007; Harvie et al, 2012). However, this improved alignment has not subsequently been shown to affect patient-reported outcome measures. Randomised controlled trials have not reported any differences in Knee Society Scores, Western Ontario and McMaster Universities Osteoarthritis Index, Oxford Knee Scores or patient satisfaction scores between the two treatment techniques (Spencer et al, 2007; Harvie et al, 2012). However, computer-assisted navigation may still be useful in the setting of extra-articular femoral deformity or in situ intramedullary devices that would preclude the use of standard intramedullary alignment guides. Proponents of computer-assisted navigation have also suggested that the elimination of intramedullary instrumentation results in a reduced postoperative systemic inflammatory response (Kuo et al, 2018). However, there are limited studies showing any long-term differences between conventional jig-based and computer-assisted navigation total knee arthroplasty.

Although the use of computer-assisted navigation for total knee arthroplasty is decreasing, robotic-assisted unicompartmental knee replacement and total knee arthroplasty is rapidly gaining popularity and more widespread use (Kayani et al, 2018a). Robotic-arm assisted total knee arthroplasty offers additional advantages compared to navigation, including haptic feedback during bone cuts, and dynamic assessment of the soft tissue envelope. Similar to navigation, robotic-arm assisted total knee arthroplasty has been associated with improved alignment compared to conventional total knee arthroplasty (Song et al, 2013; Kayani and Haddad, 2019). Robotic-assisted total knee arthroplasty is associated with improved early functional outcomes, including reduced postoperative pain, improved range of motion, reduced need for inpatient physiotherapy, and earlier hospital discharge compared to conventional total knee arthroplasty (Marchand et al, 2017; Kayani et al, 2018b). These improvements in early functional outcome measures are likely the result of reduced periarticular soft tissue injury owing to the haptic bone resection windows with robotic total knee arthroplasty (Marchand et al, 2017; Kayani et al, 2018b,c).

Kayani et al (2018a) compared bone and soft tissue injury in conventional total knee arthroplasty vs robotic total knee arthroplasty by analysing intraoperative photographs after tibial and femoral bone cuts. The authors concluded that robotic total knee arthroplasty was associated with reduced bone and soft tissue injury compared to standard jig-based total knee arthroplasty (Kayani et al, 2018a). It remains unclear how improved preservation of the soft tissue envelope with robotic-assisted total knee arthroplasty will translate to long-term functional outcome scores and component survivorship compared to conventional total knee arthroplasty. A prospective randomised control trial comparing robotic total knee arthroplasty (n=975) and conventional total knee arthroplasty (n=990) did not detect any differences in functional outcome scores, aseptic loosening, complications, and overall survivorship at a minimum of 10 years follow up (Kim et al, 2020). However, this was a single-surgeon study that used a robotic device that is unable to quantify soft tissue tension. The ability to dynamically assess the soft tissue envelope intraoperatively to help in balancing is a key feature in some robotic systems (Kayani et al, 2019a; Kim et al, 2020).

Achieving balanced flexion–extension gaps, equal mediolateral soft tissue tension, and limb alignment within safe ranges are important surgeon-controlled variables that influence postoperative functional outcomes and implant survivorship following total knee arthroplasty (Kayani et al, 2019b; Robinson et al, 2019). Robotic technology has enabled these technical objectives to be achieved with high levels of precision and accuracy, which are not possible with the handheld alignment guides and manual oscillating saw of conventional total knee arthroplasty. There are four main schools of thought for alignment in total knee arthroplasty: anatomical, mechanical, kinematic and functional alignment.

1. Mechanical alignment aims to achieve neutral overall alignment using distal femoral and proximal tibial resections that are perpendicular to the mechanical axes of the femur and tibia respectively (Insall et al, 1985).
2. Anatomical alignment restores neutral hip–knee–ankle angle by performing measured valgus distal femoral and varus proximal tibial resections to recreate a joint line orientation angle of 2–3° from the horizontal and brings the joint parallel to the floor during single leg stance (Hungerford and Krackow, 1985).
3. Kinematic alignment aims to restore the patient's pre-arthritis knee alignment with respect to the three axes of rotation of the knee – the primary femoral axis (tibiofemoral flexion and extension), the secondary femoral axis (patella-femoral flexion and extension), and the longitudinal tibial axis (tibial internal and external rotation) (Hollister et al, 1993; Eckhoff et al, 2005; Howell et al, 2008). With this technique, resections are based on proprietary software that determines the primary femoral axis with cylinders of best fit for the femoral condyles preoperatively, or determined intraoperatively by resecting the femoral condyles symmetrically after estimating the cartilage and bone loss (Roussot et al, 2020).
4. Functional alignment uses robotic technology to manipulate bone cuts and fine-tune implant positioning to achieve balanced flexion–extension gaps, equipoise in mediolateral soft tissue tension and restore the patient's native limb alignment, as guided by the periarticular soft tissue envelope. This novel technique restores of patient-specific limb alignment to within 3° of neutral overall limb alignment (Kayani et al, 2018b; Oussedik et al, 2020).

The choice of unicompartmental knee replacement vs total knee arthroplasty for medial compartment osteoarthritis is still widely debated. Proponents of unicompartmental knee replacement claim improved functional outcomes, decreased complications, and improved cost-effectiveness compared to total knee arthroplasty (Beard et al, 2019; Clement et al, 2019; Wilson et al, 2019). However, those in favour of total knee arthroplasty state that this technique has longer implant survivorship and decreased revision rates compared to unicompartmental knee replacement (Evans et al, 2019; Wilson et al, 2019). Robotic-assisted unicompartmental knee replacement offers renewed optimism as improvements in the accuracy of implant positioning may improve component survivorship and reduced outliers in limb alignment may decrease wear in the native compartments. Thus, robotic technology may help to improve revision rates in unicompartmental knee replacement. Early results for robotic unicompartmental knee replacement have been promising (Bell et al, 2016; Kayani and Haddad, 2019; Burger et al, 2020; St Mart et al, 2020). Radiographic analysis from a large randomised controlled trial comparing robotic-assisted to conventional unicompartmental knee replacement reported significantly improved implant positioning and alignment in the robotic group (Bell et al, 2016). Furthermore, a study reported that the robotic unicompartmental knee replacement does not have a learning curve effect, which offers an avenue for reducing surgical controlled errors in implant positioning as a result of low surgical case-volume (Kayani et al, 2019a). Recent registry data have shown that robotic unicompartmental knee replacement is associated with reduced revision rates at short-term follow up compared to conventional manual unicompartmental knee replacement, although the results of longer term studies on functional outcomes and implant survivorship are awaited (St Mart et al, 2020).

Through the accumulation and processing of large data sets from patients that have undergone knee arthroplasty, artificial intelligence may provide useful kinematic data that can help surgeons to deliver patient-specific surgical plans better and predict outcomes following surgery. Machine learning, which also comes under the umbrella term of artificial intelligence, describes computer systems that are capable of processing large amounts of complex data to guide and predict the output. It is further subdivided into supervised and unsupervised learning (Jones et al, 2018). Supervised learning is when data are inputted into the computer system, which then predicts the output using an algorithm. The machine uses stored data from previous cases to demonstrate the relationship between predefined input and outputs. Unsupervised learning processes use newly input data to predict patterns, such as using recorded data of implant failure over time to predicts future failure rates (Jones et al, 2018). Robotic technology offers an avenue for assessing and recording individualised patient data on knee kinematics, component positioning, functional outcomes, and implant survivorship. Artificial intelligence can then be used to select the ideal patients for surgery, create patient-specific surgical plans for unicompartmental knee replacement and total knee arthroplasty, predict clinical outcomes and implant survivorship, and identify patients at high risk of complications.

Conclusions

Robotic-assisted surgery is enabling surgeons to execute planned component positioning and limb alignment with improved accuracy and reproducibility compared to conventional unicompartmental knee replacement and total knee arthroplasty. This technology is providing new data on individualised knee kinematics, limb alignment and component positioning that was not previously possible. Computerised systems and machine learning may be able to correlate this input data to output data relating to clinical outcomes and implant survivorship. Artificial intelligence offers an avenue for using these outcomes to select the ideal patients for surgery, create patient-specific surgical plans for unicompartmental knee replacement and total knee arthroplasty, predict clinical outcomes and implant survivorship, and identify patients at high risk of complications.

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Conflicts of interest

The authors declare no conflicts of interest.

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Key points

- Robotic-assisted surgery is enabling surgeons to execute planned component positioning and limb alignment with improved accuracy and reproducibility compared to conventional unicompartmental knee replacement and total knee arthroplasty.
- Robotic technology is providing new data on individualised knee kinematics, limb alignment and component positioning that was not previously possible.
- Computerised systems and machine learning may be able to correlate input data on disease progressions and knee kinematics to output data relating to clinical outcomes and implant survivorship.
- Artificial intelligence offers an avenue for using these outcomes to select the ideal patients for surgery, create patient-specific surgical plans for unicompartmental knee replacement and total knee arthroplasty, predict clinical outcomes and implant survivorship, and identify patients at high risk of complications.

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