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Five historical innovations that have shaped modern orthopaedic surgery

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Abstract

Throughout history, many innovations have contributed to the development of modern orthopaedic surgery, improving patient outcomes and expanding the range of treatment options available to patients. This article explores five key historical innovations that have shaped modern orthopaedic surgery: X-ray imaging, bone cement, the Thomas splint, the Pneumatic tourniquet and robotic-assisted surgery. We will review the development, impact and significance of each innovation, highlighting their contributions to the field of orthopaedic surgery and their ongoing relevance in contemporary and perioperative practice.

Keywords

Innovations / Orthopaedic Surgery / History / Advancements

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Introduction

Orthopaedic surgery has a long and rich history, and over the years there have been numerous innovations that have significantly impacted the field. These innovations have played a critical role in improving patient outcomes, reducing recovery times and making surgeries less invasive. One of the most significant historical innovations that has shaped modern orthopaedic surgery is the X-ray. Discovered in the late 19th century, X-ray technology has allowed orthopaedic surgeons to visualise the skeletal system and diagnose pathology, as well as being an essential tool in the diagnosis and treatment of fractures and dislocations.

Another critical innovation that has shaped modern orthopaedic surgery is bone cement. Developed for use in orthopaedics in the 1950s by Sir John Charnley, bone cement has revolutionised joint replacement surgery.

The Thomas splint revolutionised the treatment of soldiers in the First World War and is still in use today, allowing the alignment of the fractured femurs and preventing tissue damage. The pneumatic tourniquet introduced in the early 20th century allowed orthopaedic surgeons to perform surgeries with greater precision and reduced the risk of excessive bleeding.

Much more recently, robotics surgery has opened up new frontiers in orthopaedic surgery. From robotic-assisted joint replacement surgeries to spine surgeries, robotics has significantly improved patient outcomes and reduced recovery times. It has also made surgeries less invasive, reducing the risk of complications and improving the overall patient experience.

These five historical innovations have significantly shaped modern orthopaedic surgery, and their impact continues to be significant today. They have paved the way for safer, more effective and less invasive treatment options, and have improved patient outcomes and quality of life. This article aims to review the development, impact and significance of each innovation, highlighting their contributions to the field of orthopaedic surgery and their ongoing relevance in contemporary and perioperative practice.

X-ray imaging

X-ray imaging is the most frequently used radiological investigation throughout orthopaedics and forms the cornerstone for the diagnosis of bony fractures and other musculoskeletal pathologies. X-rays were first discovered in 1895 by Wilhelm Conrad Röntgen,

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Figure 1 The first medical X-ray image, 'Hand mit Ringen' taken by Röntgen of his wife Anna Bertha Ludwig's left hand (Frankel 1996)

Professor of Physics in the University of Wurzburg, Germany. Röntgen generated the first medical radiological photograph to be published by holding his wife's hand between a vacuum tube and a plate coated in barium platinocyanide (Figure 1). These rays were termed X-rays based on the mathematical concept of the unknown quality denoted 'X' (Dunn 2001). The X-rays were quickly used by surgeons in the diagnosis of fractures and the localisation of foreign bodies (Frankel 1996). The first application to orthopaedics was noted in the *Lancet* in 1886 as a case report titled 'The discovery of the bullet lost in the wrist by means of Röntgen rays' (Jones & Lodge 1896). For his remarkable discovery, Röntgen was given the Nobel Prize in Physics in 1901. This concept was further advanced by Marie Curie during the First World War under the direction of the French Ministry of war in 1915. Curie developed the first mobile X-ray unit allowing for the detection of bony fractures and foreign bodies in wounded soldiers (Grammaticos 2004).

The use of X-rays to investigate the musculoskeletal system is now used routinely intraoperatively to assess bones and joints in real time through a process known as fluoroscopy. These real-time images are captured through repeated pulses of radiation that pass through the tissue and are collated by the image intensifier. The mobile X-ray machine used in theatre is known as a C-arm, due to the C-shape of the X-ray tube and image intensifier (Toppenberg et al 2020). There are many benefits to the use of intraoperative fluoroscopy, namely, accurate fracture reduction and alignment, which is key in the management of both simple and comminuted fractures as poor reduction and alignment increases the risk of malunion resulting in early arthritis, reduced functionality and decreased quality of life (Nair et al 2021).

As we step into the future of orthopaedics, we find artificial intelligence (AI) software has been used to detect fractures on both X-ray and computed tomography (CT) images, for example, a study by Olczak et al (2017) showed that their best-performing AI model detected fractures of the ankle, hand and wrist with the same accuracy as senior orthopaedic surgeons shown the same images. Another study by Urakawa et al (2019) showed that their best AI model was able to detect fractures of the hip on anteroposterior (AP) radiographs with a greater accuracy than five orthopaedic surgeons who were shown the same images. It is clear that X-ray capabilities have moved at a staggering pace across the last century, from Röntgen's first radiograph, to intraoperative dynamic images achieved using the C-arm, and through to AI models detecting fractures with a greater accuracy than surgeons.

Exposure to radiation and the requirement for protection

Medical staff are currently the single largest group in the United Kingdom who are exposed to manmade sources of radiation (Narain et al 2017). Exposure to ionising radiation is now commonplace in the life of any individual working in an orthopaedic theatre, driving the necessity for personal protective equipment (PPE), namely, lead aprons, thyroid shields and radiation dosimetry (Gowda et al 2019). However, this level of protection has not always been afforded to those working closely with X-rays. Within a year of the discovery of X-rays, reports of pathologies occurring as a direct result of exposure began to surface. One such report (Boice et al 2020) came from Thomas Edison in 1896 after finding his work with X-rays had led to skin ulceration and hair loss of his assistant Mr Dally. Mr Dally went on to die from metastatic carcinoma in 1904 and is thought to be the first death attributed to X-ray exposure (Sansare et al 2011).

Bone cement

Polymethyl methacrylate (PMMA) is commonly known as bone cement and is widely used for implant fixation in various orthopaedic arthroplasties and trauma surgeries. The first bone cement used in orthopaedics is widely accredited to the famous English surgeon, John Charnley, who in 1958, used it for total hip arthroplasty (THA). Since then, there have been many developments in cementing techniques in arthroplasty surgery.

Components of bone cement

The components of bone cement include a liquid monomer called methyl methacrylate (MMA) and a powdered MMA–styrene co-polymer. These two

Table 1 Components of acrylic bone cement using the acronym MISCPOC

M	Monomer	Methyl methacrylate (MMA) – Liquid
I	Initiator	N,N-dimethyl-p-toluidine (DMPT)
S	Stabiliser	Hydroquinone
C	Colourant	Chlorophyll
P	Polymer	Polymethyl methacrylate (PMMA) – Powder
O	Opacifier	Barium sulphate ($BaSO_4$) or Zirconium dioxide ($Zr0_2$)
C	Catalyst	Benzoyl peroxide (BPO)
A	Antibiotics	Gentamycin, vancomycin

components undergo an exothermic reaction, which produces heat that is dissipated. During this process, the liquid monomer polymerises around the prepolymerised powered particles. To facilitate the reaction and reduce the activation energy required, an initiator such as di-benzoyl peroxide (BPO) is added to the powdered component, while an activator such as N,N-dimethyl-p-toluidine (DMPT) is included in the liquid component. Hydroquinone is also added to the liquid monomer to prevent spontaneous polymerisation caused by light or heat exposure during packaging. In addition, contrast agents like barium sulphate ($BaSO_4$) and zirconium dioxide ($Zr0_2$) are added as an opacifier to make the cement radiopaque. Antibiotic adjuvants, such as gentamycin and vancomycin, can also be added to prevent infection, but they must be able to withstand the temperatures generated in the exothermic reaction (Bargar et al 1983). Chlorophyll is used as a colourant to allow immediate contrast between bone and cement. The formulations and constituents of various bone cements differ, resulting in different handling properties (refer to Table 1) (Kuehn et al 2005).

Cementing techniques

Significant progress has been made in cementing techniques since Sir John Charnley introduced cemented hip arthroplasty in 1972. Over time, as the properties of bone cement have become better understood, cementation techniques have evolved (Charnley 1960, 1970). Currently, there are three generations of cementing techniques (refer to Table 2). Changes in the generations of cementing techniques have primarily been influenced by the anatomical region of bone being prepared to accept the cement, cement preparation and cement delivery.

In the first-generation cementing technique, the finger-packing technique was used to apply pressure to the cement and ensure adequate cement penetration into the bone interface. This technique involved manually pressurising the cement using digital force from the proximal to distal component of the femoral canal. The two components of the cement were hand mixed in an open bowl. Early basic and clinical studies demonstrated improved fixation strength of cement when the cancellous bone of the canal was cleared of debris. These findings led to the development of the second-generation cement technique.

The second-generation technique involved the use of a distal intramedullary cement restrictor, inserted less than two centimetres distal to the tip of the stem. The restrictor facilitated greater penetration of cement into the cancellous bone proximal to the intramedullary restrictor and reliably prevented cement leakage (Hungerford & Krackow 1981). In this generation, all cancellous bone near the endosteal surface of the femur was removed. In addition, a cement gun was used to fill the femoral canal in a retrograde manner, creating higher cement pressure distally than proximally.

The third generation of cementing technique incorporates modern concepts such as pulsatile lavage, stem centralising devices and vacuum-centrifugation mixing of the cement. These techniques have been shown to reduce long-term revision rates (Wixson et al 1987). In this generation, the cement is inserted in a retrograde manner and pressurised. The prosthesis is inserted using an introducer, with distal and proximal centralisers to ensure a uniform cement mantle. These modern techniques help achieve an adequate level of cement penetration and reduce the degree of cement porosity that may compromise the cement mantle (Ritter & Thong 2004).

Table 2 A summarised description of the evolution of the three generation cementing techniques

First generation	Second generation	Third generation
Limited bone-bed preparation	Bone-bed preparation (bulb syringe irrigation or drying)	Pulsatile lavage for thorough bone-bed preparation
Unplugged femur	Distal femur cement restrictor	Improved distal cement restrictor
Stiff cement and 'finger packing technique'	Retrograde cement application with cement gun	Retrograde cement application via cement gun
Digital pressurisation	Femoral and acetabular cement pressurisation	Femoral pressuriser and acetabular pressuriser
Hand mixing of cement	Open atmosphere cement mixing by hand	Vacuum mixing, stem centraliser, cement spacers

New modern concepts in the third generation of cementing technique involve pulsatile lavage, stem centralising devices and vacuum centrifugation mixing of the cement. These have shown to reduce the long-term revision rates (Bökeler et al 2022). In this generation, the cement is inserted in a retrograde manner and the cement is pressurised. The prosthesis is inserted using an introducer, with distal and proximal centralisers to ensure a uniform cement mantle. These modern techniques help achieve an adequate level of cement penetration and reduce the degree of cement porosity that may compromise the cement mantle (Ritter & Thong 2004).

Modern-day uses of bone cement

The use of PMMA has extended to filling bone voids resulting from the debridement of erosive bone lesions like Giant Cell Tumours, providing structural support and denaturing microscopic traces of the lesion through its exothermic reaction (Kim et al 2022). Despite these benefits, PMMA is non-biodegradable, lacks osteoinductive or osteoconductive properties and cannot integrate biologically with surrounding host bone. While new techniques are under development, PMMA continues to have a role in non-joint areas.

In recent years, PMMA has been utilised in vertebroplasty or kyphoplasty procedures in the spine, where it is injected into the vertebral bodies to maintain their height and structure (Vasconcelos et al 2001). This can be achieved through techniques such as balloon kyphoplasty or vertebroplasty, and the cement offers suitable compressive strength. There have been recent advancements in robotic techniques for this procedure, with good outcomes reported (Neumann et al 2022).

Thomas splint

The Thomas splint is a well-known and widely used medical device in the field of orthopaedics, particularly in the management of femoral fractures. Its history can be traced back to the 19th century when Hugh Owen Thomas, a renowned British orthopaedic surgeon, developed the concept and design of the splint (Ellis 2021). His nephew, Sir Robert Jones (Figure 2), formally introduced the use of the Thomas splint during the First World War, which significantly reduced the mortality and morbidity rates of femoral fractures in injured soldiers (Batchelor 1969). The success of the Thomas splint in the military setting led to its adoption in the civilian medical field (Liew et al 2017).

History of the Thomas splint

During the First World War, high mortality rates were observed in patients with compound fractures of the femur due to the shearing forces of high velocity missiles. The inadequacy of inferior splintage methods such as bolsters and slings and other treatments was recognised (Ellis 2007). To address this problem, Sir Robert Jones, an orthopaedic surgeon from Liverpool with prior expertise in the organisation of casualty services, introduced the use of the Thomas splint (Figure 3). The Thomas splint, originally designed by his uncle Hugh Owen Thomas, who is considered by many as the 'father of British orthopaedic surgery' (Robinson & O'Meara 2009). The concept and design of the splint were described by Thomas himself in 1876 with the aim of stabilising femoral fractures and reducing infection rates (Jones 1953).

Stretcher bearers were trained to apply the splint blindfolded, and patients were admitted to specialised dedicated 'femur wards' at base hospitals. Prior to the introduction of the Thomas splint, amputation was the preferred treatment option for saving the lives of patients with femoral fractures (Ellis 2021). However, with the use of the splint, the mortality rate of femoral fractures was significantly reduced from 80% to 15.6% in 1,009 cases by the end of the First World War (Gray 1919).

Use in modern-day orthopaedics

In modern-day orthopaedics, the Thomas splint remains an essential piece of equipment in emergency and orthopaedic units in hospitals worldwide. Its basic design has changed little in the 133 years since its original description by Hugh Owen Thomas (Cope 1995). The popularity of its success in a hospital setting can be attributed to its simplicity, ease of use and effectiveness in immobilising fractures of the lower limb, as well as the significant reduction in mortality and morbidity rates it provides (Henry & Vrahas 1996).

Furthermore, the use of the Thomas splint outside of the hospital setting has allowed prehospital practitioners to efficiently manage open and closed femoral fractures, reduce major haemorrhage and facilitate patients' transport to hospitals (Abarbanell 2001). Although various modifications have been made to the original design, they have not significantly deviated from the original design of the Thomas splint (Figure 4). In modern-day practice, the splint remains essential in the initial management of femoral shaft fractures (Liew et al 2017).

Pneumatic tourniquet

The history of surgery is to a large extent written around the record of its technical advances. A pneumatic tourniquet is a relatively simple instrument when compared with many of the more complicated mechanical devices in the modern operation theatre. Nevertheless, it has played a significant role in making

Figure 2 Sir Robert Jones, a General Director of Military Orthopaedics on the Western Front during the First World War (Batchelor 1969)

Figure 3 Stretcher bearers practising the application of the Thomas splint during the First World War (Robinson & O'Meara 2009)

possible the precise operations of present-day orthopaedic, plastic and vascular surgery. It has been around probably longer than most people realise and probably longer than any records may suggest.

The tourniquet can be traced back to 200 BC and the Roman Empire (Klenerman 1962). It was used on soldiers and civilian patients with the priority of saving lives rather than limbs, and leather instruments or bronze rings were used for this purpose. Not much changed over the next 1,500 years until the use of a stick to twist the constricting bandage, which has been ascribed to Hilden (1560–1624), Morell (1674) and James Yong (1679) (Noordin et al 2009). In 1718, Jean-Louis Petit displayed his invention to the Royal Scientific Academy of Paris (Figure 5) and used the word 'tourniquet à vis,' which was derived from 'turnere' a vis,' a French word that means turning (Desiron 2007).

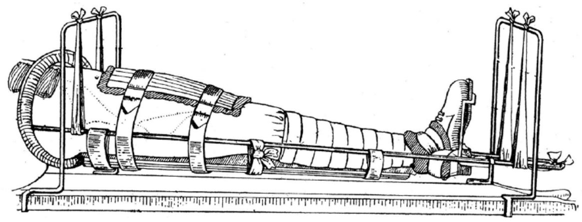

Figure 4 The injured individual lying on a stretcher, a Thomas splint has been applied over their footwear and clothing. This showcases how the splint was hung from both proximal and distal bars to enhance their comfort (Liew et al 2017)

Lister probably was the first surgeon who used a blood-free field created by a tourniquet in a surgery other than for amputation. In his case of a wrist excision, he declared that the limb must be kept upright for three minutes before using a tourniquet for the blood to exit (Fu Kuo-Tai 2010). The next tourniquet that was commonly used was a flat rubber bandage, which was first introduced by Johann Friedrich August von Esmarch, Professor of Surgery at Kiel University, in 1873. He proposed that the rubber bandage be avoided if the soft tissues contain pus as this was likely to spread the infection (Noordin et al 2009), which is now accepted as a rule. His rubber bandages are still used today to plump up a vein to help take blood and in wider versions to exsanguinate a limb before surgery (Figure 6).

The pneumatic tourniquet first appeared in 1904 attributed to Harvey Cushing who invented it with inspiration from blood barometer after dissatisfaction with the Esmarch band (Cushing 1904). With this introduction came a means of monitoring and controlling the tourniquet pressure.

In 1908, August Bier invented a new method to anaesthetise the limb (the Bier's block – most commonly used for distal radius fracture manipulation) by using a tourniquet placed above the site and injecting the anaesthetic into the vein (Reis 2008).

Within the last 40 years, there have been many important improvements in the technology of tourniquets. These modifications have led the US Food and Drug Administration to classify pneumatic tourniquets as Class I medical devices (indicating that they present minimal harm to the user and do not present a reasonable source of injury through normal use).

Pneumatic tourniquets are used in an estimated 15,000 orthopaedic and non-orthopaedic surgical procedures daily in the United States and elsewhere, facilitating operations by reliably establishing a bloodless surgical field with a high level of safety. The modern microcomputer-based tourniquet system was invented in 1981 by McEwen (McEwen 1981). The elements of that first automatic tourniquet system are depicted in Figure 7.

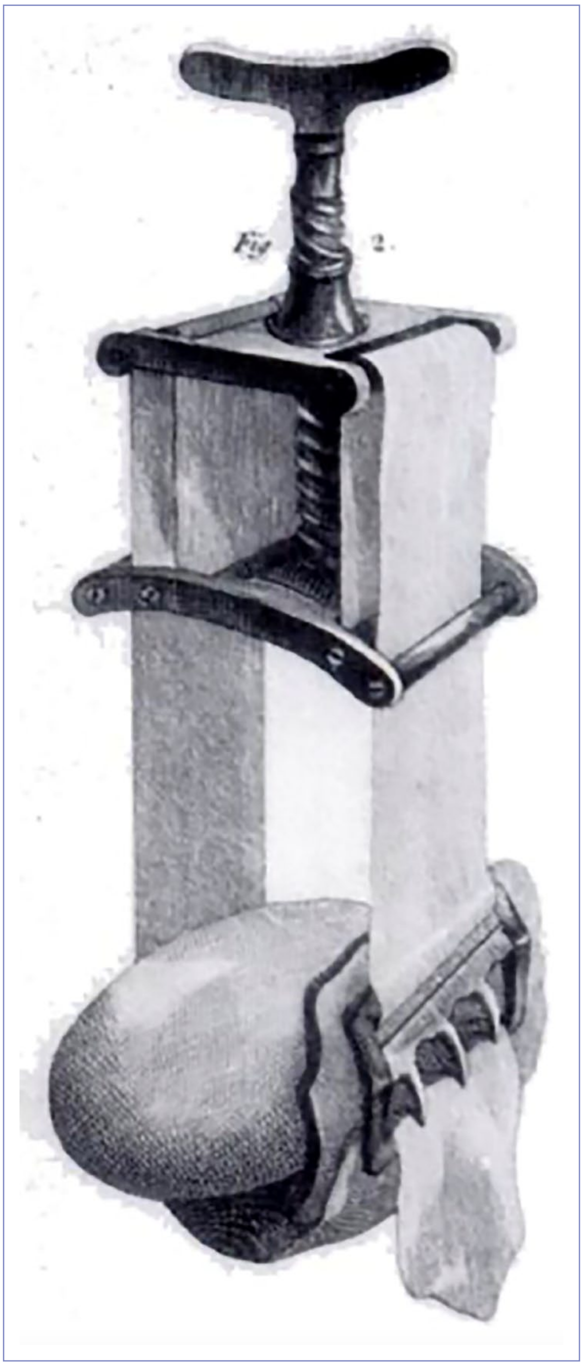

Figure 5 The petit type of tourniquet (1798) (Desiron 2007)

Modern tourniquet system with elements that have improved safety, accuracy and reliability. Microprocessor technology allows precise sensing and regulation of the real-time cuff pressure, enabling accurate indications of cuff pressure and lapsed time to be provided visually; produces audio-visual alarms automatically in the event of a wide range of hazardous conditions and allows automatic estimation of limb occlusion pressure (LOP). Improved cuff designs allow cuff pressure to be applied effectively to encircled limbs with a wide range of sizes and shapes (McEwen et al 2002a, b, Pedowitz et al 1993, Tredwell et al 2001, Younger et al 2004)..

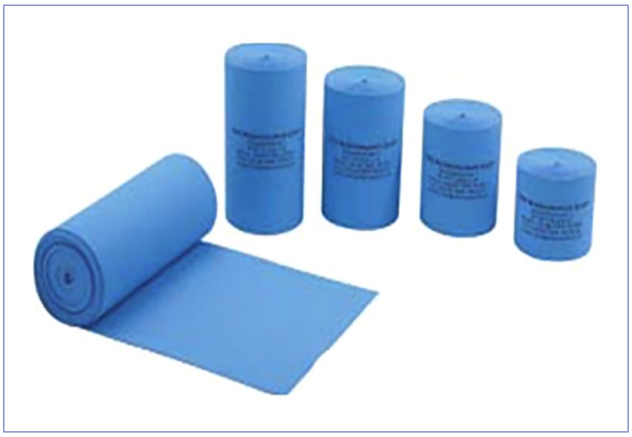

Figure 6 The modern-day Esmarch bandage (Noordin et al 2009)

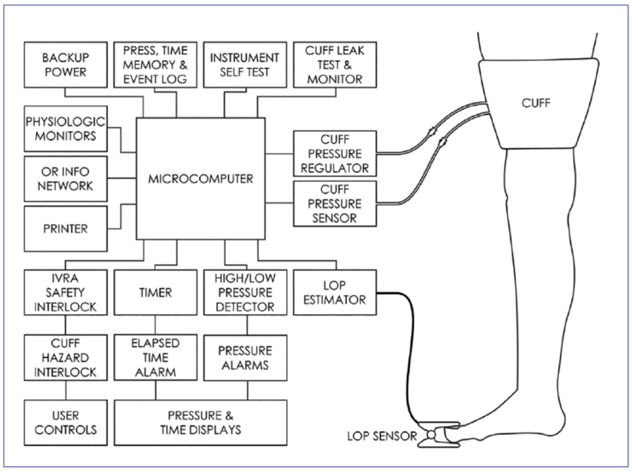

Figure 7 The elements of that first automatic tourniquet system (McEwen & Inkpen 2002)
IVRA: intravenous regional anaesthesia; OR = operating room.

The tourniquet of the future

The concept of setting the optimal tourniquet pressure for each patient is an ideal but would require measuring limb occlusion pressure immediately prior to inflation of a surgical tourniquet. However, a single measurement represents a static limb occlusion pressure and safe margins would be required to account for relevant intraoperative variations in the patient's physiology during an operation. In the future, safer tourniquet systems using lower tourniquet pressures could perhaps be developed by monitoring those physiologic variations intraoperatively and estimating a dynamic limb occlusion pressure on the basis of those variations (McEwen & McGraw 1982, Tuncali et al 2006). To a large extent, the risk of tourniquet-related nerve injuries is addressed in surgical practice by minimising tourniquet time, but in the future this may be dealt with by new technology that helps to minimise the tourniquet pressures that are required, and by new types of pneumatic tourniquet cuffs that help to minimise cuff pressure levels and gradients. Given the increasing rate of obesity, new designs of tourniquet cuffs that allow arterial blood flow to be stopped effectively at the lowest possible tourniquet pressures and gradients may be helpful for the increasing numbers of obese patients. In addition, recent studies suggest that in the future it may be feasible to further reduce the risk of neurological injuries by directly monitoring axonal excitability in nerves beneath tourniquet cuffs (Ikemoto et al 2009, Kuwabara 2009). This may allow surgical staff to be alerted promptly to potential nerve-related hazards before injury occurs.

A futuristic concept for further increasing tourniquet safety and effectiveness may come from a current military project. The US Defense Advanced Research Projects Agency (DARPA) is sponsoring the Deep Bleeder Acoustic Coagulation (DBAC) programme with the goal of developing a non-invasive, automated ultrasonic system for the detection, localisation and coagulation of deep bleeding vessels (DARPA nd). A spin-off benefit of the DARPA DBAC programme might be the development of low-cost ultrasonic sensor arrays that could be useful for accurately detecting, monitoring and controlling the occlusion of arterial blood flow beneath surgical tourniquet cuffs.

Robotics

In comparison to the above innovations, robotics is still a relatively new and evolving field within orthopaedics. The word 'robot' was created by the Czech playwright Karel Čapek, derived from the Czech word for forced labour, and describes a machine able to function automatically (Knowles 2005). Robots have been around in medicine since the 1980s and in orthopaedics since 1992 (Lang et al 2011). Within orthopaedics, the use of robots has been reported in knee, hip, foot and ankle, shoulder, spine and trauma surgery (Karthik et al 2015).

ROBODOC (Integrated Surgical Systems, Davis, CA, USA) was the first robot used for orthopaedic surgery (Bargar et al 1998). It was created to improve positioning of the femoral implant in uncemented THA, as initial results showed a high failure rate. Initially, 'locator pins' were inserted under local anaesthetic; then, the patient underwent a CT scan for preoperative planning. The surgeon then planned their implant choice and final position within the computer software. Intraoperatively, the robot was brought in to burr the femoral canal to the shape and size of the implant as determined by the preoperative planning. A 'pinless' technique was later developed (Bargar 2007). The first trial of this robot reported greater average blood loss (1189ml vs 644ml) and surgical time (258 vs 134 minutes) compared to the control group (Bargar et al 1998).

Robotic surgery can be described as haptic (guided by the surgeon) or autonomous (Lang et al 2011). In haptic surgery, the surgeon is actively driving the system. This works by using CT scans preoperatively to create a computerised model of the joint and the surgeon plans the bony cuts, size and position of the implants on this model. During the operation, the surgeon uses bony landmarks as reference points for the system which then combines this with the preoperative model to identify the resection area, or cutting zone, for the robot. While the surgeon is guiding the instruments, the monitor shows the computerised model. As a safety measure, the instruments will stop if the surgeon tries to go outside of this cutting zone (Lang et al 2011). In autonomous surgery, once the initial setup is completed by the surgeon, the robot takes over and completes their part of the surgical procedure independently. For safety, there is an emergency off button that the surgeon can use if required (Lang et al 2011).

Those who advocate the use of robotic surgery in orthopaedics do so because there is increasing evidence to show better alignment, particularly for unicompartmental and total knee replacements, and better component positioning (Bargar et al 1998, Cobb et al 2006, Honl et al 2003, Karthik et al 2015, Song et al 2011). However, none of the studies have shown statistically significant improvements in the knee scores between the robotic and conventional groups. Up to now, there is also no convincing evidence that this translates into lower revision rates.

With new technology comes concerns for its safety and efficacy. As previously mentioned, there was greater blood loss and longer operating times with the ROBODOC, and this isn't the only study to report longer operating times. It is reported by the authors to be down to the initial learning curve with new technology (Bargar et al 1998, Karthik et al 2015). Other studies have reported complications such as nerve injury, heterotopic ossification, dislocation, abductor muscle tendon detachment, patellar tendon rupture, patella dislocation, postoperative supracondylar fracture, patella fracture, revision and superficial infection (Honl et al 2003, Park & Lee 2007). In addition to these complications, an obvious downside to robotics is the price, with robotic systems reported to cost between £290,000 and £2 million (Karuppiah & Sinha 2018). On top of this is the cost of preoperative imaging, equipment and maintenance. Perhaps if there was more evidence that robotic surgery in trauma and orthopaedics leads to lower revision rates and improved patient outcomes, then the high initial costs could be justified. Overall, the use of robotics in orthopaedic surgery is a rapidly advancing field that has the potential to improve patient outcomes and revolutionise the way that orthopaedic surgeries are performed.

Conclusion

In conclusion, the history of orthopaedic surgery is rich with innovations that have had a significant impact on patient outcomes and treatment options. From the advent of X-ray imaging to the development of robotics, the five key historical innovations explored in this article have played a crucial role in shaping modern orthopaedic surgery. The advancements in bone cement, the Thomas splint and the pneumatic tourniquet have provided effective solutions to long-standing challenges in orthopaedic surgery, while X-ray imaging and robotics have revolutionised diagnostic and treatment capabilities. As orthopaedic surgery continues to evolve, these innovations remain relevant and continue to inform contemporary practice.

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Declaration of conflicting interests

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