

Trends and developments in hip and knee arthroplasty technology

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Abstract

The developments in hip and knee arthroplasty over recent years have aimed to improve outcomes, reduce complications and improve implant survival. This review describes some of the most interesting trends and developments in this important and fast-moving field. Notable developments have included ceramic hip resurfacing, mini hip stems, cementless knee replacement and the wider adoption of the dual mobility articulation for hip arthroplasty. Advances in additive manufacturing and the surface modification of joint replacements offer increasing options for more challenging arthroplasty cases. Robotic assisted surgery is one of the most interesting developments in hip and knee surgery. The recent growth in the use of this technology is providing data that will help determine whether this approach should become the standard of care for hip and knee arthroplasty in the future.

Keywords

Orthopaedics, hip arthroplasty, total knee arthroplasty, osteoarthritis, robotic care

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Introduction

Hip and knee total joint arthroplasty are effective surgical treatments for the management of arthritis. Joint replacement surgery involves the resection of the degenerative joint and replacement with syntenic components which reconstruct the worn joint surface allowing pain free mobilisation. Hip and knee implant design and development over the past century has predominantly focussed on reducing mechanical wear and enhancing implant fixation. This approach has been very successful, with modern bearing surfaces and implant coatings providing far more durable solutions than those available at the advent of modern hip and knee arthroplasty in the 1960s. With an increasingly active and longer living population and a trend for joint replacement earlier in life, the work on improving implant survival continues. However, increasingly the latest developments in hip and knee arthroplasty implant technology have concentrated on technologies hoping to improve patient outcomes through strategies to mimic more natural kinematics and optimised implant positioning. This review will highlight several of what we consider are the most significant technological developments with respect to implant design and assistive technology in hip and knee arthroplasty.

Hip resurfacing

Hip resurfacing is perhaps a surprising choice to consider as a new technology given that resurfacing implants have been used in various guises for well over 40 years.¹ Hip resurfacing surgery provides an alternative to the more conventional hip replacement for the treatment of hip arthritis. Hip resurfacings (Figure 1) preserves femoral bone stock compared to conventional total hip arthroplasty. The larger size femoral head articulation results in a biomechanically more stable joint.³ The advantages of larger metal on metal articulations, were not without cost, with certain implants demonstrating high revision rates predominantly due to the generation of metal debris leading to adverse reactions in some patients. The increased revision rate has negatively affected the perception of hip resurfacing.¹ However, hip resurfacing has been

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Figure 1. Metal-on-metal Birmingham Hip Resurfacing.²

shown to offer lower dislocation rates and superior functional outcomes for younger active patients compared to conventional total hip arthroplasty.^{4,5} Whilst metal on metal hip resurfacing remains an option for active males with larger hips, it is no longer considered appropriate for men with smaller femoral head sizes and never appropriate in women. Therefore, recent advances have focused on new alternative bearing couples for hip resurfacing. Novel approaches to address this issue include the use of ceramic on ceramic or metal on polyethylene articulations.

To date there are at least two ceramic hip resurfacings undergoing early clinical trials. The H1 ceramic non-porous non-cemented hip resurfacing developed by Embody Orthopaedic Limited (London, UK) is presently under evaluation as part of a multicentre observational study which commenced recruiting in September 2017.⁶ This ten-year follow-up study aims to evaluate the safety and efficacy of the prosthesis. The ceramic on ceramic ReCerfTM developed by MatOrtho (Leatherhead, Surrey UK) is currently awaiting certification in the UK, however the first device was implanted on the 24th September 2018. While early clinical data are not yet available for either implant, cadaveric studies have evaluated the mechanical properties of the ReCerfTM arthroplasty which have reassuringly demonstrated comparable deformation between a standard metal component and the novel ceramic acetabular component.⁷

Although ceramic on ceramic articulations do have favourable wear characteristics, there is concern regarding the potential for squeaking and the brittleness of ceramic bearings. Furthermore, there is the potential for unwanted reduction in bone density around the implanted ceramic implants, a phenomenon known as stress shielding.⁸ To address these potential



Figure 2. Tri-Lock mini stem.¹¹

issues the metal on cross-linked polyethylene (MoX) hip resurfacing was developed by Derek McMinn. To date, 88 MoX resurfacings have been implanted.⁹ This articulation has the potential to minimise metal ion release and with the lower stiffness of polyethylene there is reduced potential for stress shielding seen with stiffer acetabular components, though this is at the possible risk of increased volumetric polyethylene wear.¹⁰

Mini stem total hip arthroplasty

One of the advantages of hip resurfacing is the preservation of femoral bone stock in comparison to conventional total hip replacement. Partly as a consequence of the decline of metal on metal hip resurfacing and due to the increased popularity of minimally invasive surgical approaches, there has been a trend for the development of smaller femoral prostheses (Figure 2) that aim to preserve bone stock and load the proximal femur in a more physiological manner.¹²

Differences between mini-stem philosophies and designs has meant that systematic reviews and meta-analyses of the varying implants has been challenging.¹³ However, a systemic review by Lidder et al. including 15 studies demonstrated implant survival of 98.6% at a mean follow up of 12 years.¹⁴ However, the learning curve for mini stems appears to be greater than for conventional total hip arthroplasty with variation in femoral neck canal diameter and the need for a stable press fit requiring a low tolerance for error in implant positioning and surgical technique. Click or tap here to enter text.¹⁵ Evaluation of these stems is

ongoing with a recently published randomised trial into stability of mini stem implants at 2 years with radiostereometric analysis demonstrating femoral component migration comparable to standard length stems.¹⁶

Dual mobility total hip arthroplasty

The use of dual mobility articulations, whilst not novel having first been developed by Gilles Bousquet in 1974,¹⁷ have in recent years been adopted more frequently for use in primary total hip arthroplasty.¹⁰ Dual mobility implants (Figure 3) consist of a small metal or ceramic head that is enclosed but mobile within a larger polyethylene head which in turn articulates with the acetabular component of the joint replacement. Many national joint registries have noticed an increasing trend in the use of Dual Mobility articulations, the latest report from the American joint replacement registry reported an increase use of Dual mobility to 6.9% of all total hip arthroplasties.¹⁹ There is presently some suggestion that dual mobility articulations should be offered as a mainstream alternative to more traditional articulations.²⁰ Given the advantageous and well-established increase in stability associated with a dual mobility articulation,^{4,5} the trend for increased utilisation of the technology may be related to increasing recognition of the relevance of unfavourable spinopelvic mobility and its implications in the stability of total hip arthroplasty. There has also been growth of their use in high risk groups such as those with neuromuscular conditions or cognitive impairment.²¹ However, there are concerns related to volumetric polyethylene wear, intraarticular dislocations and there is limited data on long term survivorship.[Click or tap here to enter text.](#)²² Retrieval studies to date have been reassuring with respect to wear rates.^{23,24}

The use of a dual mobility articulation also has a role in revision surgery given their increased stability. They have been used successfully for femoral only revision of large head metal on metal hip arthroplasty²⁵ as well as for alternative revision indications with dual mobility articulations demonstrating superior survivorship compared to fixed-bearing implants.²⁶

Cementless knee total knee arthroplasty

One of the more promising areas in the development of knee arthroplasty implants has been in the development of cementless methods of fixation. Traditionally total knee arthroplasty prostheses have been implanted with polymethyl methacrylate cement as a grout interdigitating with the cancellous bone and the implant surface. Cementless total knee arthroplasty has the advantage of avoiding an extra interface with the



Figure 3. Dual Mobility Total hip arthroplasty.¹⁸

hope this could reduce rates of wear and loosening. However, initial pressfit designs were associated with high early failure rates with a series demonstrating 8% aseptic loosening rate at a mean follow-up of 11 years. [Click or tap here to enter text.](#)^{27,28} Recent developments in cementless technology and implant design have led to a new generation of cementless total knee arthroplasty implants. A recent randomised study has reported early follow-up data comparing patients receiving cemented or cementless implants. At two years both showed equivalence in patient reported outcome scores and degree of subsidence. Cementless implants were associated with a shorter operative time. It should be noted that patients aged over 75, those with a body mass index over 40 kg/m², evidence of grossly osteoporotic bone or bone defects were excluded.²⁹ A meta-analysis of cementless knee arthroplasty encompassing 7 studies with a mean follow-up of 6 years found encouraging results in terms of survivorship, though studies again used highly selective inclusion criteria.³⁰ The relatively selective nature of studies of cementless knee arthroplasty implants makes it difficult to draw conclusions on the appropriateness of this technology in the general population.³¹

Cementless technology can be successful in the knee. The Oxford[®] cementless partial knee replacement from Zimmer Biomet (Warsaw, Indiana USA) has demonstrated excellent survivorship with limited concern regarding osseointegration.^{32,33}

While Early cementless knee replacement designs with high failure rates left many younger patients with significant lysis and bone loss.⁷ Overall the initial results of the newer class of cementless knee replacement are encouraging, though further long-term studies

are required before this technology supplants cementation.

Implant surface modification

Advances in the shape of implants is often at the forefront of prosthetic joint development. However, with the growing challenge of prosthetic joint infection and the aim of further improving osseointegration, modification of the implant surface topography and chemistry has provided a new avenue in implant design with promising results.

While several materials are used for the production of joint replacements, Titanium has been the focus for the advances in surface modification. Titanium alloy, commonly Ti-6Al-4V, is frequently used in orthopaedics owing to its favourable biomechanical properties and amenity to surface modification.³⁴ Topographical modifications aim to improve osteointegration by encouraging ongrowth or ingrowth of bone. These techniques have focused on the microscale and use roughening processes such as grit blasting or plasma sprayed surface coatings.³⁵

The recognition of the potential effects of nanoscale surface topography have led to the development of techniques to modify the surface topography on a much smaller scale. These approaches include methods such as electron beam lithography and anodisation creating nanoscale tubes, pits, pores and pillars on the implant surface that can be favourable to osteoconduction and consequently osteointegration.

The process of surface modification on the nanoscale level apart from promoting osteointegration, also has the potential to affect the interaction between bacterial pathogens and the implant potentially mitigating the devastating consequences of prosthetic joint infection.^{36–38} Since the discovery of the adverse role of biofilms associated with bacterial infection,³⁹ alteration of implant surfaces either via nanotopographic patterns or elution of bactericidal ions such as silver have provided an appealing approach. Modulation of a Titanium surface nanostructure has been demonstrated to reduce the adhesion of several bacterial species that are responsible for over 50 percent of prosthetic joint infections.⁴⁰ Preventing bacterial adhesion helps inhibit early bacterial colonisation, impede evasion of the immune system and maximise the effectiveness of antibiotics given in the perioperative period. The techniques have looked to nature for inspiration and have recognised that through evolution over millennia several natural surfaces have developed ways to reduce bacterial colonisation. Therefore, scientists have recreated on a nanoscale the features of dragonfly wings and shark skin (Figure 4), the dragon fly wing with nanopillars has a self-cleaning surface

reducing bacterial adhesion as well as bacteriocidal properties.⁴²

An alternative to modifying the implant surface topography, is to engineer the implant to elute substances with antimicrobial properties. The most widely studied technique is silver nanoparticles. These antimicrobial nanoparticles leached from implants have been demonstrated to be effective against *Escherichia coli* and *Staphylococcus aureus* for up to 10 days in vitro.⁴³ However, there is some concern regarding elution of nanoparticles and local tissue toxicity. These technologies are in the translational stage but are likely to find their initial justification for use in terms of risk and cost-benefit in megaprosthesis replacements for revision joint replacement or sarcoma surgery.⁴⁴

Additive manufacturing and custom implants

The majority of joint replacements undertaken utilise 'off the shelf' components which provide a satisfactory solution for the majority of patients. The customisation of implants provides the opportunity to provide a personalised solution for hip and knee joint reconstruction. While the majority of arthroplasty cases probably do not require such a tailored approach. More complex revision surgery with substantial bone loss, tumour surgery and surgery following major trauma may benefit from such a strategy. As technology has advanced and individual implant costs are reduced, the customisation of implants is expected to rise.⁴⁵

Customisation of femoral implants for total hip arthroplasty aims to improve the match between the native anatomy and the implant to reduce stress shielding as well as more accurately restore the joint centre of rotation. The earlier generations of implants were customised from standard radiographs and manufactured using standard Computer Numerical Control (CNC) machining before coating to encourage osteointegration. The series of customised hip replacements published by Muirhead-Allwood et al. in 2010 demonstrated survivorship of 98.2% at 13.2 years for the use of customised hip stems which was felt comparable to the best standard femoral components.⁴⁶ Dessyn et al. demonstrated similarly good follow-up at 20 years from their series of 232 hip replacements with 96.6% survivorship in a younger cohort of patients published more recently.⁴⁷

Newer additive manufacturing techniques have made it simpler to produce complex customised implants including porous structures with variable density and stiffness to minimise bone loss and remodelling due to stress shielding.^{48,49} The majority of experience

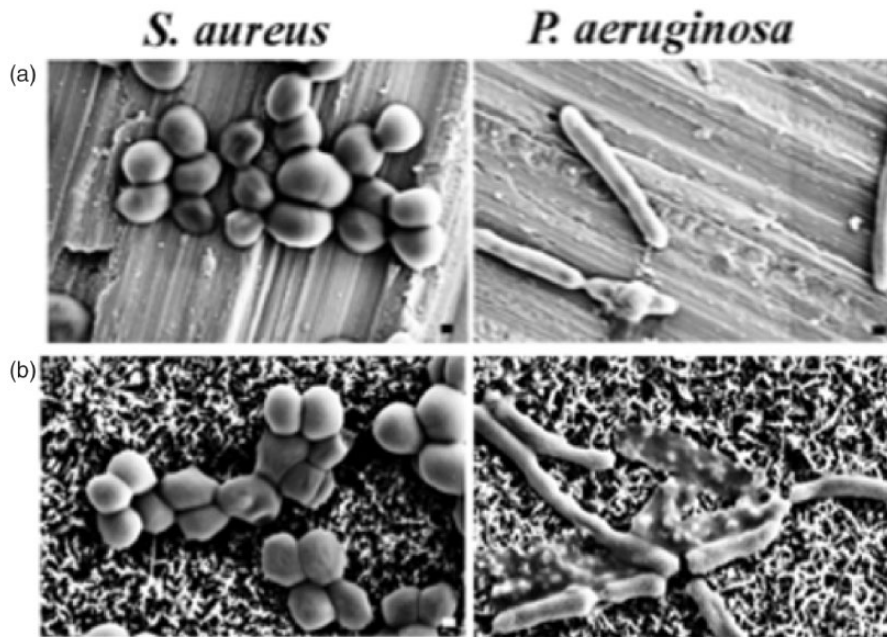


Figure 4. Effect of *S. aureus* and *P. aeruginosa* growth on control titanium surface a) and the nanopatterned surface fabricated via hydrothermal etching to mimic the surface architecture of dragonfly wings. A reduction in attachment and viability of bacteria was seen in the modified surface.⁴¹

of custom additive manufactured implants comes from acetabular revision surgery. A recently published review into the use of a custom triflange acetabular components by Martino et al. found in 17 studies that the combined complication rate was 29% with dislocation being the most common (11%) followed by infection (6%).⁵⁰ The aseptic loosening rate of the 579 hips included with a mean follow-up of 57.4 months was 3.1%. These complex cases demonstrated outcomes that were comparable with other reconstructive options. While these custom solutions often provide an appealing option for challenging cases it should be remembered that due to their individualised nature these implants cannot provide a track record. Since 2002 the Orthopaedic Data Evaluation Panel (ODEP) have evaluated the outcomes for standard joint replacements ensuring that they remain safe and effective as well as providing a benchmark for newer implants. Such ratings are unavailable for custom implants and surgeons should ensure that patients are aware that data on survivorship is unavailable.

Robotic assisted surgery

The decision regarding the intraoperative placement of components for hip and knee replacements has traditionally relied on anatomical landmarks and referencing jigs to guide component orientation. One of the

most exciting developments in joint arthroplasty is the use of robotic assisted hip and knee arthroplasty to support the surgeon in these critical decisions. Robotic assisted joint replacement surgery has been around for a while, with systems available in the 1980s.⁵¹ Robotic assisted surgery is an evolution of navigated joint replacement surgery where computer assistance helped to guide the positioning of instruments and implants. Robotic surgery takes this a step further with the robot helping to position instruments or controlling the function of tools to ensure that bone resection matches the planned operation. The surgical plan may be based on the patient's own anatomy derived from a CT scan or increasingly "image-free" systems are used which map a series of anatomical landmarks from the patient peri-operatively to a stored catalogue of joint morphologies that are used to plan the procedure.

There has been significant growth in the use of robotic assistance over the past decade, particularly in the USA. In the New York region between 2008 and 2015 just over 5% of all hip and arthroplasty procedures were either robot or navigation assisted.⁵¹ Much of the recent drive for increased use of robotic technology (Figure 5) has come from the engagement of the major hip and knee implant manufacturers. The Mako system by Stryker (Kalamazoo, Michigan USA), the Navio/BlueBelt from Smith & Nephew (Andover, Massachusetts USA) or ROSA from Zimmer Biomet



Figure 5. Stryker Mako Robotic System Chai W, et al. Use of Robotic-Arm Assisted Technique in Complex Primary Total Hip Arthroplasty.⁵²

(Warsaw, Indiana USA) are increasingly widely available.

There is good evidence that robotic assisted surgery can help to improve implant positioning accuracy compared to manual placement in both hip and knee arthroplasty surgery. Lawson et al.^{50,53} demonstrated statistically significant improvement in acetabular component positioning placed within 5° of the target alignment with the use of robotic guidance compared to standard techniques in a case series of 100 patients. Illgen et al.^{51,54} found similar improvement in acetabular component placement for total hip arthroplasty accuracy using robotic assistance compared to manual placement.

Bell et al. demonstrated improved accuracy in implant position with robotic assisted surgery compared to standard techniques in unicompartmental knee replacement in a randomised study of 120 patients.⁵⁵ Several other studies for unicompartmental knee replacement and total knee replacement have demonstrated that accuracy of implant alignment can

be improved with robotic assisted surgery.^{56–59} In knee arthroplasty, robotic assistance can include tensioning devices to ensure accurate ligament balance when using a gap balancing technique.⁶⁰

It is clear that robotic assistance can help surgeons achieve a particular plan, though are there other benefits? Bukowski et al. reported lower blood loss and superior functional outcome scores with robotic assistance in their comparison of 100 robotic assisted and 100 manual total hip arthroplasties.⁶¹ In total knee arthroplasty, robotic assistance has been shown to protect soft tissues in comparison to manual techniques.⁶² However, overall there is little data currently to suggest that robotic assisted surgery leads to superior functional outcomes. A meta-analysis by Karunaratne et al. looking at the outcomes of 14 studies of robotic hip and knee arthroplasty did not detect a difference in functional outcomes between robotic assisted and manual surgery.⁶³ None of the included studies, which were noted to all be of low or very low quality, showed any difference in pain, quality of life or satisfaction with surgery. In a meta-analysis of manual and robotic assisted unicompartmental knee replacement Zhang et al. did not show a difference between the groups in terms of functional outcomes, revision rate or range of motion.⁶⁴

Robotic assisted surgery has additional associated costs including hardware purchase, theatre time and radiology related outlay for image guided systems. Given the absence of clear clinical benefit to date, cost-effectiveness has been a barrier to wider adoption. However, studies have suggested that high volume centres using robotic assisted surgery could be cost effective for unicompartmental knee replacement.^{51,65} Further studies will be needed to demonstrate if robotic assisted surgery should be considered the gold standard for hip and knee arthroplasty.

Conclusion

This review has focussed on several of the most exciting strategies and developments in hip and knee arthroplasty as well as our evolving understanding of the use of robotics in joint replacement. While these developments focus on separate aspects of joint arthroplasty; they are united in their overarching aim of improving patient outcomes. There is recognition that innovation, whilst essential, needs to be balanced with the critical role of doctors to protect patients from the potential harmful effects of novel technologies being brought to market without a prior rigorous evaluation. Surgeons should resist the temptations of these technological advances until such evaluation has been undertaken often in the form of well conducted and reviewed clinical trials. The rule of diminishing return and the

fact that the majority of joint replacement surgeries provide excellent outcomes means that these advances need to demonstrate convincing long-term data to justify their adoption over established technology.

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