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INTEGRATED STUDY MASTER'S THESIS

Opportunities to improve accuracy of radiological planning for THA. A literature review.

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1. INTRODUCTION TO THE LITERATURE REVIEW

1.1 LITERATURE REVIEW'S OBJECTIVES

Total hip arthroplasty (THA) has become one of the most effective interventions in orthopedic surgery. Radiological planning is a fundamental step in total hip arthroplasty (THA). It serves as a roadmap for the surgeon and allows to predict important surgical decisions before stepping into the operating room. This literature review aims to examine how planning can be made more accurate and what that may mean for surgical results. Despite advances, problems such as improper sizing, misalignment, or positioning can still occur because of limitations in techniques. It may result in complications affecting the long-term success of this procedure (19,21,24). The review tries to bring out where the opportunities for improvement are. This is based on existing evidence and recent developments in technology.

The review also draws attention to the correlation between quality preoperative planning and improved postoperative outcomes. Calibration techniques and templating software are also discussed for enhancing precision in radiological planning. While these tools are increasingly incorporated into routine use, there are still challenges around how they are standardized and clinically used. Lastly, this review discusses how training, protocol development, and future innovations may better facilitate planning accuracy and outcomes (24,65,88).

1.2 OUTLINE OF KEY THEMES

1.2.1 PREOPERATIVE PLANNING

Preoperative planning sets the stage for the entire surgical procedure. It requires an exact evaluation of radiographs to select the appropriate size and orientation of the implant and to recover crucial anatomy such as femoral offset and limb length. Good preparation before surgery enables the surgeon to undertake the procedure with more confidence and efficiency. This also minimizes the need for intraoperative recalibrations and decreases the incidence of complications. Preoperative planning is not only a technical practice. It needs to be individualized, as clinical evidence shows that the anatomy and patient needs are not uniform (19,22,24).

1.2.2 RADIOLOGIC TEMPLATING

Templating is the stage where the plan is laid out. This process includes assessing the radiographic images of what the prosthesis is expected to fit like. Calibration methods are critical to this process since radiographs are distorted by magnification. External calibration markers are some of the tools that attempt to balance this distortion. However, several further factors can disrupt, like improper placement of markers, differences in patient anatomy, or bad image quality (31,33,34). In this part of the review, we look at modern templating tools, analyze their reliability, and discuss digital innovations that may resolve some of the challenges.

1.2.3 POSTOPERATIVE OUTCOMES

Lastly, the postoperative outcome is related to what happens after surgery. Even if the operation is a success, the quality of the outcome is determined by whether the implants work well in day-to-day life. Preoperative plan and templating accuracy are often directly correlated with things such as implant alignment, leg length equality, and joint stability. Imaging still plays a role, even after the surgery is done. Follow-up radiographs identify early complications such as loosening or wear. Patient-reported outcomes (PROMs) are additional means of assessing satisfaction, mobility, and pain after surgery to provide a more holistic assessment of success (41,60,62).

1.3 SIGNIFICANCE OF THESE THEMES IN THE CONTEXT OF THA

These three themes are connected and pivotal to the success of any hip replacement. A minor planning error can lead to significant problems. These range from little instability to implant failure. Meanwhile, dramatic improvements in imaging, templating software, and calibration techniques are enabling surgeons to perform with greater precision than ever. Given that the number of hip replacements continues to rise worldwide, any improvements in radiological planning may ultimately help to provide safe and effective patient care. Greater accuracy doesn’t just equal fewer complications; it means faster recoveries, higher satisfaction, and less revisions (24,65,88). These Processes need to be understood and improved for the future functionality of THA.

2. BACKGROUND AND IMPORTANCE OF HIP REPLACEMENT

2.1 HISTORICAL CONTEXT

2.1.1 EVOLUTION FROM EARLY TECHNIQUES TO MODERN THA

Introduced by Sir John Charnley in 1960, Total Hip Arthroplasty (THA) was labeled the "Operation of the Century" for its profound impact on the field of Orthopedic Surgery and its positive effect on quality of life (1). Coxarthrosis itself has been known since antiquity, still surgery for its treatment only began with the advent of surgery. Evidence from skeletal remains indicates that different types of arthritis have afflicted humans for thousands of years, as pathological changes consistent with arthritic diseases have been found in Saxon, medieval, and Roman excavations. Even Homo sapiens neanderthalensis fossils show evidence of notochord and articular degeneration, highlighting a long-standing challenge to human health posed by joint pathologies (2).

Hip arthroplasty has had its beginnings since the late 19th century, when Themistocles Gluck first performed the first reported hip arthroplasty in Germany in 1891. He had an ivory femoral head hemiarthroplasty (1). In the first part of the 20th century, early hip replacements were interpositional arthroplasties utilizing an array of different biological materials including skin, fascia lata, and even pig's bladder (1).

At roughly the same time, Dr. Ban Saw, then chief of orthopedics at Mandalay General Hospital in Burma, used custom-made ivory prostheses to operate on patients with fractures of the neck of the femur. By 1969, he had published results for 300 patients, aged 24 to 87. Notably, 88% of these individuals returned to sports and cycling in weeks following surgery (1).

The evolution of modern hip arthroplasty began with Smith-Petersen's introduction of the Vitallium mold arthroplasty, a shift in prosthetic material that provided enhanced strength and function (1). Wiles went on to perform the first total hip arthroplasty (THA) in the United Kingdom in 1938, with the surgical technique subsequently refined (1).

But it was modern hip arthroplasty in the 1960s by the British surgeon Sir John Charnley that changed things. Charnley presented several revolutionary concepts, such as low-friction arthroplasty, polymethyl methacrylate (PMMA) cement as a mechanism of fixation and high-density polyethylene as a bearing surface. While some of Charnley's techniques have changed throughout the years, the principles he laid down remain fundamentally unchanged and can be found at the basis of most modern THAs (1).

The chemical composition of bone cement has remained unchanged since its introduction but the technique by which it is applied has been significantly improved (3). Cementing Methods can be categorized into three generations:

First-Generation: The original cementation methods consisted of hand mixing, finger packing and insertion by hand (3). However, soon after it was found that optimizing bone preparation — scrubbing and cleaning the cancellous bone of debris, considerably increased the strength of fixation (3).

Second-Generation: These innovations included the use of a cement restrictor, enhanced canal irrigation and drying, and retrograde filling of the cement. These changes resulted in better performance compared with older methods by increasing stability and durability (3).

Third-Generation: All second-generation refinements are included in modern cementing techniques as well, in addition to vacuum mixing, pressurization, and centralizing the cement mantle around the femoral stem. This method of mixing cement in a vacuum leads to less voids in the cement, and thus improves the mechanical properties. The use of pressurization enhances the penetration depth of the cement into cancellous bone and improves fixation. In addition, the use of centralizers provides for a more homogenized cement mantle, to reduce direct implant-bone contact and to avoid void spaces in the cement mantle that may in turn compromise long term stability (3).

2.2 CLINICAL IMPORTANCE

2.2.1 PREVALENCE OF CONDITIONS LEADING TO HIP REPLACEMENT

Total hip arthroplasty (THA) has emerged as one of the most frequently performed and successful operations in contemporary orthopedic surgery. It is used for a variety of severe and debilitating hip disorders. Among the common causes of hip degeneration that need total hip arthroplasty (THA) are osteoarthritis, avascular necrosis (AVN), post-traumatic sequelae, inflammatory arthritis and osteopetrosis. Although each of these conditions affects the hip joint differently, they all have one thing in common: progressive damage that eventually leads to loss of function.

Osteoarthritis: Hip replacement surgery is mostly performed for osteoarthritis (OA). Approximately 10% of adults aged 45 and older in the United States are affected by hip osteoarthritis (4). As the disease advances, joint pain and stiffness exacerbate, making something as basic as walking or climbing stairs a challenge (4). For many patients, non-operative treatments like physical therapy, pain management, and activity modifications help for a period. When these are no longer sufficient, total hip replacement remains the most favorable alternative. With over 90% of patients experiencing pain relief and restored mobility (4), THA has an impressive success rate. At the same time, surgeons are refining the procedure. Studies have shown that cementless hip implants in which the acetabular component is made of ceramic, have better functional and radiological results than cemented implants in older patients over two years (5). With an aging population and rising life expectancy, the demand for THA will only continue to increase (4).

Avascular Necrosis and Hip Joint Damage After Trauma: The most common cause for hip replacement is osteoarthritis, but it isn't the only one. Avascular necrosis (AVN) is one of the other indications for THA, particularly in younger patients (6). This process occurs when the blood supply to the femoral head is interrupted resulting in avascular necrosis (AVN) (6). AVN is the most common reason for hip replacement surgery in certain populations followed by post-traumatic conditions (6). AVN can progress much faster than osteoarthritis, and may even require surgical intervention at earlier stages (6).

Meanwhile, post-traumatic hip conditions develop after fractures, dislocations, or prior surgeries. These cases are complex because trauma may modify the joint biomechanics. Scar tissue, deformities, and prior implants can complicate the surgery, emphasizing the need for thoughtful preoperative planning (6). Another consideration is muscle strength and function and how different hip conditions affect these. For instance, patients with AVN normally do not lose as much muscle structure as those with osteoarthritis who have age-related wasting of their musculature (6). In post-traumatic cases, anatomical irregularities from prior injuries or surgical procedures may also present mechanical obstacles to optimal joint alignment (6).

Inflammatory Arthritis: Inflammatory arthritis can lead to destructive changes in the hip. This category of diseases, which includes rheumatoid arthritis and ankylosing spondylitis, results from autoimmune inflammation that slowly deteriorates the surfaces of the joint (7). Interestingly, the need for hip replacement surgery has declined over the past two decades in patients with inflammatory arthritis. This is mainly attributed to the advances in the treatment of patients with disease-modifying anti-rheumatic drugs (DMARDs), which can slow disease progression. However, patients do still progress to end-stage joint damage, which requires THA (7)

Osteopetrosis: While osteoporosis causes a deficiency in the bone, osteopetrosis is a rare genetic deformation in which the bones become abnormally dense but brittle. Consequently, the significant risk of developing osteoarthritis and fracture non-union that may necessitate a hip replacement are high (9). In patients with osteopetrosis, the abnormal quality of bone and reduced size of intramedullary canals make performing THA especially challenging. Survivorship data are favorable (89% survivorship at 10 years) but these patients have a 58% reoperation rate and a 44% risk of periprosthetic femoral fractures (9).

2.2.2 IMPACT ON PATIENT QUALITY OF LIFE AND MOBILITY

Degenerative changes leading to hip pain commonly interfere with daily life and reduce independence, consequently, a number of patients pursue orthopedic intervention (4). Not being able to walk and stand or even do customary things can cause social isolation and reduced mental well-being (4). THA is already well-established as an excellent treatment option, alleviating pain and restoring functional capability, independence, and mental stability (10). Gaining mobility after surgery is especially difficult for elderly patients with neuromuscular dysfunction. By improving early recovery and enabling fundamental motor performance, THA brings optimism and provides a strong motivation for rehabilitation, both necessary for a successful result in the long run (10). THA for hip degeneration and fractures has been established as a gold standard treatment, and although, the technique of fixation varies, most patients experience substantial pain relief and mobility (11).

Patient satisfaction is a major measure of THA success and is directly related to postoperative pain alleviation and mobility. DMC-THA patients for example have reported higher satisfaction due to improved physical activity and the ability to walk with confidence (10). Similar studies investigating bone cement versus no cement fixation techniques demonstrated slightly better results in short-term pain relief and the ability to carry out self-care with uncemented fixation; nevertheless, ultimate high satisfaction rates for both methods were achieved (11). Most of the time, moving pain-free is what leads to good outcomes for the patient not the actual surgical technique used (11).

2.3 TECHNOLOGICAL AND SURGICAL ADVANCEMENTS

2.3.1 OVERVIEW OF CURRENT PROSTHETIC MATERIALS AND DESIGNS

Over the last few decades total hip arthroplasty (THA) has evolved remarkably with regards to superior implant longevity, reduced complications, and better patient outcomes. THA is still a very effective procedure for pain relief and functional improvement in patients with osteoarthritis and avascular necrosis, but research efforts are ongoing to minimize the risk of dislocation, implant loosening, infection and limb length discrepancy. First, areas of innovation primarily focus on novel prosthetic materials, implant designs, and minimally invasive surgical methods utilizing computer-assisted navigation and robotic technologies. The advent of HXLPE (highly cross-linked polyethylene) has been a particularly significant advancement, as it has significantly minimized wear-associated complications and prolonged the life span of hip prosthesis. Likewise, navigation and robotic-assisted methods have enhanced the precision with which implants are placed, reducing the likelihood of dislocation and other complications. The number of THA procedures is expected to increase over the next several decades, and it is crucial for the materials and surgical techniques to continue to experience refinements that optimize long-term outcomes (12).

Development of better materials for prosthetics have also been important in improving the durability and function of THA implants. One of the most successful innovations related to polyethylene is highly cross-linked polyethylene (HXLPE), which has shown decreased wear when compared with conventional ultrahigh-molecular-weight polyethylene (UHMWPE). In a ten-year radio stereometric study of HXLPE versus UHMWPE, HXLPE showed a tenfold decrease in wear rates, confirming reduced volumetric penetration. The adoption of HXLPE has also reduced the risk of osteolysis, a prominent cause of implant loosening, which allows for longer-lasting implant fixation. The introduction of this material has also allowed for larger femoral heads to be utilized, thereby enhancing joint stability and lowering dislocation rates. Due to its low wear properties, HXLPE is now routinely used in THA, especially in young and active patients who demand prostheses with a relatively longer life. (12,13).

Metal alloys have always played an essential role in the construction of THA implants due to the mechanical strength, biocompatibility and corrosion and wear resistance. Due to their high durability and resistance to deformation, cobalt-chromium (Co-Cr) alloys are widely used as femoral heads. The implant uses a material that promotes easy movement in combination with polyethylene liners, which reduces friction and wear of the implant. Cementless femoral stems and acetabular components are often made from titanium alloys, particularly titanium-6Al-4V, because they are lightweight, have good mechanical strength, and promote bone ingrowth. This promotes implant anchoring and minimizes the risk of loosening, which is especially beneficial for younger patients who need long-term fixation. Stainless steel was one of the first materials chosen for orthopedic implants, but gradually this material was replaced because of its corrosion and lower biocompatibility. Nevertheless, stainless steel devices are still used in some regions and are used for fracture fixation rather than long-term hip implants (14).

Ceramics have gained interest as an alternative bearing for THA, in view of their excellent hardness, biocompatibility, and low wear compared with traditional metal-polyethylene combinations. The implementation of ceramic-on-ceramic (CoC) bearings in the 1970s was in response to a need to combat polyethylene wear and related osteolysis. But concerns about implant fracture and squeaking were associated with early CoC implants. Consequently, ceramic-on-polyethylene (CoP) bearings developed as a popular alternative that uses the wear resistance of ceramic with the robustness and ductility of polyethylene (12,14).

Besides material enhancements, implant design modifications have led to improvements in stability and durability of THA over time. Larger femoral heads have greatly improved joint stability by raising the head-neck ratio, which decreases the chance for impingement and decreases dislocation rates (15). The improved wear properties of HXLPE also enabled surgeons a stronger adoption of larger femoral heads, especially in high demand patients who need a greater range of motion (12). Porous metal coatings have been popularized over the years to further improve fixation of implants. The explanation to this is that the porous titanium surfaces allows the bone to grow into the implant, it forms a more stable long-term bond between the implant and the surrounding bone, this so called osseointegration. This has been especially valuable in cementless THA, where successful biological fixation is vital to longevity of the implant (14,15).

Advances in bearing surfaces have also played a significant role in the success of modern THA implants. In the past 20 years, our understanding of bearing combinations has changed vastly:

polyethylene liners have increased, while metal-on-metal (MoM) articulations have decreased. The early generation of MoM bearings became popular in the late 1990s due to their low volumetric wear rates and large diameter head/acetabular cup components, but have fallen out of favor because of concerns regarding systemic metal ion release and consequent soft tissue reactions (12). When looking at market trends, ceramic-on-polyethylene bearings are increasingly being adopted, representing 11% in 2007 and grew to 50.8% in 2014. A survey of hip and knee surgeons highlighted this finding further and reported that an overwhelming majority of surgeons now prefer polyethylene-based bearings, many utilizing ceramic femoral heads to minimize the complications associated with corrosion (12).

2.3.2 INNOVATIONS IN SURGICAL TECHNIQUES AND THEIR OUTCOMES

Total hip arthroplasty (THA) has witnessed great modifications in surgical techniques as well as implant engineering, providing for enhanced patient outcomes and prolonged implant survival. As the need to perform THA increases, innovations have been established regarding robotic and computer-assisted surgery, minimally invasive techniques, and patient-specific instrumentation.

Robotic and Computer-Assisted Surgery: The integration of robotic technology and computer-assisted navigation into THA is a big advancement. They offer intraoperative information and assist in the proper positioning of the components, especially regarding leg length, femoral offset, and combined anteversion (12,16). Robotic-assisted THA (RA-THA) can utilize preoperative three-dimensional imaging and real-time intraoperative metrics to optimize implant positioning on a patient-specific level. This may enhance implant durability and diminish postoperative complications (12). Although robotic THA has demonstrated radiographic advantages, long-term clinical improvement in quality of life and function are still being evaluated (16). Moreover, robotic-assisted approaches are likely to become even more advanced through the application of machine learning and artificial intelligence to improve both preoperative planning and intraoperative decision-making. However, these advantages of robotic THA have yet to be demonstrated in a cost-effective manner, thus presently limiting widespread adoption. Long-term data will be required to justify its routine use in clinical practice (16).

Minimally Invasive Approaches: Besides robotic surgery, minimally invasive techniques for THA have also attracted attention, trying to minimize postoperative pain, shorten hospital stay, and decrease recovery time. One of the latest techniques is the introduction of direct superior approach (DSA), which can provide functional and radiological advantages. Although preliminary registry data indicates reduced revision rates due to dislocation, the existing data is insufficient to prove long-term efficacy and safety (17). Nonetheless minimally invasive techniques have been developed to support hip preservation surgery (e.g. hip arthroscopy, periacetabular osteotomy). These techniques have led to better surgical results for diseases such as femoroacetabular impingement (FAI) and congenital hip malformations, delaying the development of osteoarthrosis and the need for THA (13).

Patient-Specific Instrumentation: Conventional THA is primarily an unguided procedure that depends on surgeon experience and standard implant designs that are not necessarily matched to each patient's unique anatomy. To overcome this limitation, patient-specific instrumentation (PSI) and customized THA implants were developed, which provide a tailored means to better restore patient anatomy. PSI is based on CT-derived three-dimensional imaging data used to create individually orientated femoral stems and acetabular components to adapt them better to the facture-affected hip. This strategy could minimize complications related to the implant, such as limb-length discrepancies, inadequate femoral offset, and impingement-related dislocation (18).

Overall, there have been persistent improvements in material and surgical techniques that have led to remarkable improvements in both physical and clinical outcomes following THA with more durable implants, lower complication rates, and higher patient satisfaction. Challenges like implant-related infections, cost-effectiveness, and the reliable anatomical reconstruction of everyone's unique anatomy still exist and require further investigation (12,16,18). As demand for THA is predicted to continue rising, there is a need to address these remaining challenges to sustain the efficacy and accessibility of the procedure (12).

3. PREOPERATIVE PLANNING IN HIP REPLACEMENT

3.1 ROLE AND OBJECTIVES

3.1.1 DEFINITION AND GOALS OF PREOPERATIVE PLANNING

Preoperative planning is a critical component of total hip arthroplasty (THA) to provide a systemized approach to surgery, minimize operative variability, and improve patient outcomes. It is in these cases that a thorough analysis of the clinical and radiographic findings is made so that the surgeon can create an operative plan based on the anatomy of the patient and their functional needs (19). The thorough planning process involves taking into consideration standard radiographic films with known magnification, recognizing anatomical landmarks suitable for component placement, and evaluating the ideal size and orientation of the implant to restore joint function (19). This step is especially important since there is not one prosthesis that fits all, as bone quality, activity level, and anatomical variations must be taken in mind (20). In contemporary hip arthroplasty, meticulous preoperative planning improves surgical accuracy, decreases complications, and contributes to reproducible, predictable products (19).

The main purpose of the preoperative planning is to facilitate visualization for the surgeon about the procedure that may influence the surgical approach and thereby improve efficiency during the procedure. The implant templates are overlaid on the radiographic image to provide clinicians with an appropriate size and position of the prosthetic components. The acetabular component is positioned according to the ilioischial line, teardrop, and superolateral acetabular margin to achieve sufficient bone coverage and restore the hip rotation center (19). On the femoral side, templating is performed for both cemented and cementless implants to achieve optimum limb length and femoral offset, as these directly affect hip biomechanics (19). Using standardized X-rays and correct magnification allows to make the procedure more predictable and efficient by improving implant selection and placement (21).

The planning of the procedure beforehand allows for a high level of precision regarding accurate selection of implant sizes and positioning, limiting intraoperative guesswork and enhancing the fit of each component. In studies assessing preoperative planning accuracy, acetabular component size can be accurately predicted in 83% of patients, whereas 99% of patients are within a ±1 size deviation. Similarly, femoral component sizes were predicted correctly in 78% of cases, and accurately within one size deviation in 99%. Besides proper selection of implant size, preoperative planning will help to ensure proper alignment and restoration of limb length, minimizing the risk of postoperative discrepancies (22). Digital preoperative planning softwares have also advanced accuracy of predictions. Computer-assisted design (CAD) and digital templating tools are proven to help increase both implant size selection and surgical accuracy (23,24).

A central theme of preoperative planning is to reproduce the native biomechanics of the hip joint to achieve optimal stability, mobility, and longevity of the implant (20). It is well recognized that implant selection and positioning equalizes limb length and restores femoral offset and femoral center of rotation which leads to a balanced joint (20,22). Being able to accurately reproduce biomechanics is therefore essential, as incorrect placement of prosthetic components can result in malalignment, gait abnormalities and a higher risk of complications (20). Detailed planning allows surgeons to evaluate bone stock, fixation of implants, and potential anatomical obstacles, and choose the appropriate type and mode of fixation of the implants. However, because each patient has unique anatomical features, a one-size-fits-all approach is not applicable and personalized planning becomes crucial to establish the optimal postoperative function (20).

The use of pre-operative planning allows the surgeon to visualize the complexities in three dimensions which decreases the risk of complications during surgery and results in a more accurate and efficient surgical approach. Another benefit of proper planning is the ability to highlight acetabular abnormalities, limb length discrepancies, and areas of poor bone quality so that alternative strategies can be adopted when necessary (19). The advantage of preoperative planning has been established by studies that proved a decrease in surgical time, less need for intraoperative adjustments, and lower rates of malposition (25). In addition to that, surgeons may use advanced imaging and digital planning tools to anticipate sources of impingement, instability, and soft-tissue irritation during the surgery, potentially leading to decreased rates of postoperative complications including dislocation, progressive component wear, and implant loosening (19,24). One study found preoperative planning the leading factor in achieving the correct center of rotation placed within 2 mm of where it was planned preoperatively in 45% and within 4 mm in 91% (22).

The comprehensive preoperative planning aims to compliment the surgical efficiency, better patient outcomes and implant longevity. It is vital as it shortens operative time and minimizes intraoperative blood loss as well as postoperative complications (24). The results of multiple studies have shown that patients who undergo computer-assisted preoperative planning are discharged early, functionally recover quickly, and have superior postoperative mobility compared to those who undergo conventional planning methods (24). Besides enhancing functional outcomes, thorough planning provides optimal placement for prosthetic components, allowing implant stability and decreased revision rates (22). As the demand for hip replacement surgeries continues to grow, improvements in preoperative planning methods will remain a significant step in improving patient satisfaction and long-term THA success (23,24).

3.1.2 THE SIGNIFICANCE OF ACCURATE PLANNING IN SURGICAL SUCCESS

While THA is highly regarded for its efficacy, success is not solely dictated by the surgeon's method of operation; accurate preoperative planning is a critical aspect of the operation that is vital to minimize complications, achieve optimal position of the prosthesis, and improve functional recovery. Due to an ageing population and a growing pool of active patients, there is an increased demand for THA, which requires better planning methods for long-term prosthetic stability and surgical success. Emergence of new technologies, such as digital templating, computer-aided design (CAD), and robotic navigation, have increasingly become integrated into clinical practice, and the importance of preoperative planning continues to enhance patient outcomes while minimizing intraoperative difficulties (24).

A crucial aspect of preoperative planning is to reduce the complications occurring from implant selection and placement. The inappropriate selection of prosthetic components can result in prosthesis loosening, fractures, and chronic pain, and has a major effect on patient quality of life and surgical outcomes (24). Good preoperative planning is especially important for a prevention of dislocation, one of the most frequent complications of THA. Modular implants, femoral head size variations and offset augmentation have also been advanced, giving surgeons means to mitigate dislocation risk; however, they need to be effectively incorporated into individualized preoperative planning (26).

Mispositioned implants can result in excessive wear, dislocation, and biomechanical inequalities, even before wear occurs, and therefore an essential goal of preoperative planning is accurate implant positioning. Adequate templating principles guide positioning and sizing of the acetabular and femoral components with the aim of restoring native biomechanics of the hip joint (19,21). This accuracy is achieved by assessment of factors including but not limited to bone quality, acetabular morphology, and femoral offset, assuring that the prosthetic components are compatible with the patient's anatomy. When performed correctly, templating can predict the appropriate implant size with one size deviation in up to 99% of cases, thus limiting intraoperative guesswork and increasing surgical efficiency (22). In addition to this, preoperative planning has increasingly emerged as a tool for maximizing stability in patients with pre-existing spinal deformities or altered spinopelvic alignment, because such patients require position adjustment of components to minimize the risk of subsequent instability and dislocation (27).

Precise preoperative planning plays a role in improving recovery time and overall functional outcomes. Research indicates that patients who receive detailed preoperative planning achieve greater hip function, low pain scores, and better satisfaction rates than those with less accurate planning (24). The critical element of recovery functionally is the restoration of limb length and joint biomechanics that directly influences gait, balance, and mobility. Misalignment of orthopedic components or incorrectly sized implants may result in limb-length discrepancy, functional impairment, discomfort and increased risk of revision surgery. Studies have shown that careful templating and digital preoperative planning contribute to limb-length equalization, leading to a more natural gait and less pain at long-term follow-up (22).

3.2 TECHNIQUES AND TOOLS

3.2.1 TRADITIONAL METHODS VS. MODERN IMAGING TECHNIQUES

Total hip arthroplasty (THA) is one of the most performed elective procedures. Preoperative planning has transitioned from traditional templating to modern imaging. This enables advanced surgical planning, as well as accurate implant selection and optimized surgical efficiency. Acetate and digital 2D templating are still in the vast majority of uses but 3D templating, computed tomography imaging and 3D modeling software, have been becoming more present because of their accuracy, especially in complex cases (21).

Acetate templating (one of the first methods) is overlaying transparent acetate templates directly onto standard radiographs to estimate the sizing of the implants and their position. Although this approach is inexpensive and time-efficient, it has multiple disadvantages such as magnification errors and decreased reproducibility compared with current digital techniques. To this day, some of the more experienced surgeons continue to use acetate templating simply because they are familiar with the technique. There have been studies demonstrating that manual planning can be performed well and that, when performed by skilled practitioners, it can compare with the results of digital templating (21).

Acetate methods of templating have predominantly been replaced by digital 2D templating, which is now the standard for preoperative planning in THA. It makes use of digital implant templates overlaid on digital radiographs providing advantages such as higher accuracy, reduced magnification errors, and improved reproducibility. An important advantage of digital templating is that it provides a permanent electronic record that can be consulted by various surgical team members and used for postoperative review or future surgeries. Various studies have also demonstrated a high consistency between the calculated implant sizes during preoperative planning and the actual sizes used (21).

An important development in preoperative planning is 3D digital templating, which uses CT-based imaging to generate high-resolution 3D models of the hip joint. Unlike conventional techniques, 3D templating allows visualization in axial and sagittal planes, helping surgeons visualize the landmarks with higher precision. This is particularly great in complex anatomy. Although it has benefits, 3D templating has not been adopted universally due to cost and technology difficulties. Its current integration with robotic-assisted surgery and intraoperative navigation however paves the way for it to be a standardized planning tool in the future (21,28).

Pre-op CT imaging has a very significant role in the three-dimensional analysis of the hip joint, which can provide better preoperative planning. This enables accurate evaluation of bone morphology, implant position, and alignment, which can be especially advantageous in complex cases. However, the concern for radiation exposure when performing CT imaging has resulted in the effort for optimization of scanning protocols. Studies have looked into various CT scanning techniques, to minimize radiation exposure while maintaining a good image quality (29).

Aside from using CT imaging, specialized three-dimensional modeling software has enabled even greater advancement of preoperative planning. Many software programs include Materialize Mimics, 3D Slicer, and Siemens syngo.via Frontier, enable highly detailed anatomical reconstructions, allowing precise visualization and planning of hip replacement surgeries (30). In addition to planning, 3D modeling software allows surgeons to simulate the positioning of the prosthetics in 3D, maximizing biomechanical restoration and minimizing intraoperative changes. Despite challenges such as cost and software availability, ongoing innovations in artificial intelligence and machine learning will likely allow 3D modeling to become a standard component of THA planning (28,30).

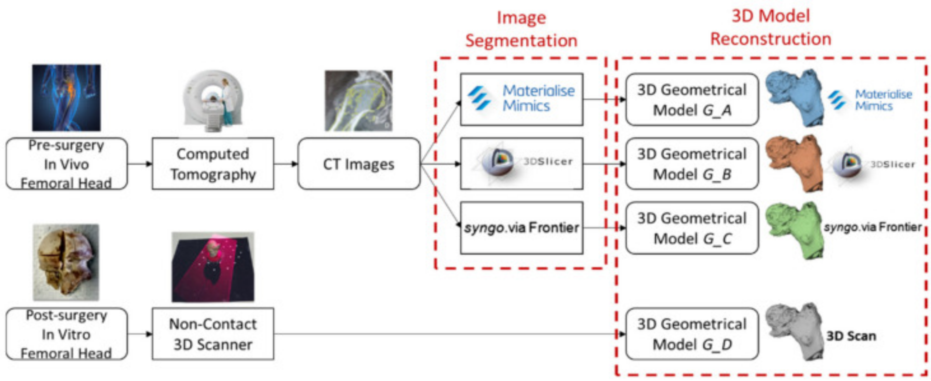

Figure 1Comparison of 3D anatomical models

3.2.2 CALIBRATION METHODS IN RADIOGRAPHIC TEMPLATING

Calibration in the context of radiographic templating consists of correcting radiographic magnification to accurately measure anatomical dimensions that allow for the selection of the appropriate prosthetic components in THA. The radiographic images are magnified depending on the X-ray source, patient size, and detector arrangement, which can affect the true anatomical dimensions and potentially misguide surgeons in their operative plans (31,32). Several methods have been tested to achieve a correctly scaled radiograph. Markers of known size are used for calibration. These could be a sphere, a coin, or a ruler. The location of the hip joint plane is estimated through palpation of the greater trochanter (32). Accurate calibration is essential since incorrect measurements can directly contribute to inappropriate implant sizing, misplaced position, and complications with the implant itself, including loosening, excessive wear, dislocation, or limb length discrepancy (31,33). Especially within obese patients or in those with proximal femoral deformities can significantly impede calibration accuracy. To address these drawbacks, alternative approaches were developed (32).

External Calibration Markers (ECM): External calibration markers are the classical method of digital templating. The markers are typically spherical and appropriately positioned at a distance from the X-ray source to adjust magnification. However, positioning is often incorrect, which is the most common cause of significant error when predicting prosthesis sizes. Errors stemming from ECM placement can lead to templating errors of 6.8% in leg length, offset, and sizing of components (34,35).

Dual Scale Calibration Marker (DSCM): To increase precision, dual scale calibration markers were created, using two individual markers of varying sizes to more accurately account for differences in magnification. While this method increases accuracy, it is restricted by the requirement for careful placement and two markers, possibly adding difficulty to clinical utilization (31).

Dual Scale Single Marker (DSSM): The DSSM approach is a new attempt to simplify the dual marker system using one marker with dual scales. This method has resulted in better accuracy than classical ECM models. A recent study found that using this type of model resulted in significantly lower differences than the ECM, suggesting that it could improve the precision of templating without increased complexity (31).

Biplanar Radiographic (EOS) System: The EOS imaging system uses biplanar radiographs obtained with a specific coin device and is considered more accurate than conventional radiographs. The EOS-based precision of the femoral head diameter resulted in excellent concurrence, especially compared to traditional modeling techniques. This is an improvement in the accuracy of preoperative templating that has reduced sizing errors and improved alignment outcomes in clinical practice (2).

Device-Adapted Magnification Factor: To address variability arising from different radiographic equipment and settings, a calibration method using a device-adapted magnification factor was implemented. This improves templating accuracy by reducing errors and standardizing the magnification factor according to the BMI of the patients and source-image distances (33).

Calibration with prosthetic femoral heads: When standardized markers are not available, using prosthetic femoral heads (typically cobalt-chrome balls) for calibration is a reliable alternative. This approach offers flexibility and reliability, especially in settings with limited resources (36).

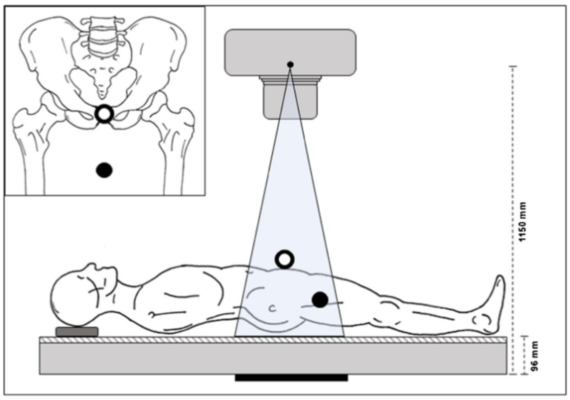

Figure 2 Positioning of DSSM (unfilled circle) and standard ECM (filled circle) marker in supine radiograph setup

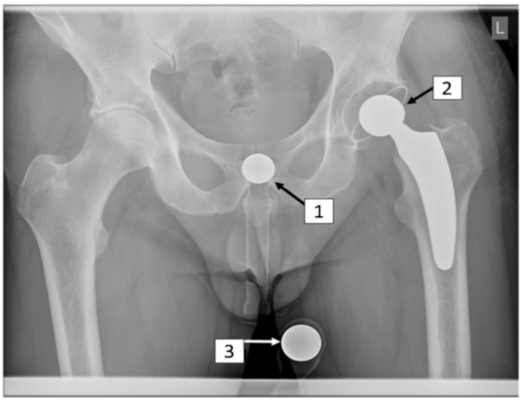

Figure 3 Anteroposterior pelvic radiograph showing left-sided short stem THA, DSSM (1), prosthesis head component (2), and standard ECM (3) in supine position

3.3 CHALLENGES IN PREOPERATIVE PLANNING

3.3.1 COMMON ISSUES IN PREOPERATIVE PLANNING

With the significance of preoperative planning comes several challenges. From limitations in radiographic imaging and errors in templating to the complexities of anatomic variation and the challenges of new technology adoption. Tackling these challenges is pivotal for maximizing surgical precision and minimizing intraoperative hazards (37).

Pelvic radiographs are an essential part of preoperative planning, and accurate radiographic imaging is crucial but difficult. In clinical practice, X-ray quality is often influenced by several factors, including exposure, orientation, and positioning of patients for the imaging. As with the previous example, standard pelvic radiographs are centered on the sacrum, however, hip templating requires that the AP pelvic view must have the beam centered on the pubis to visualize the proximal third of the femur. Moreover, distorted radiographs may underestimate or overestimate bone morphology and have the potential to mislead the selection and positioning of implants (21).

Some challenges also relate to magnification. Accurate preoperative templating of the implant hinges on the surgeon's ability to estimate the correct magnification, yet many preoperative radiographs lack accurate devices with which to measure magnification (21). Also, improper marker placement has a huge impact on the accuracy of the calibration. Errors in the placement can lead to templating inaccuracies but can also increase the risk of postoperative complications and necessitate revision surgery (34,35). Even the patient's BMI and variability of anatomy have a great impact on the accuracy of calibration, non-anatomical calibration methods can have significant templating errors (33).

Despite several modern templating techniques, accuracy has been a challenge in both manual and digital methods. Preoperative templating predicts implant size accurately in only 62% of acetabular cups, in 78% of cemented stems, and only in 42% of cementless stems. In addition, estimation errors are a common drawback of manual templating techniques, resulting in intraoperative repositioning that increases operative time as well (37). To tackle these issues, computer-assisted templating techniques (3D templating, digital planning software) have been developed. The accuracy of digital planning was reported to be very high; the implant size deviated +/- one size in 93% of acetabular components and 84% of femoral components (23).

In cases with intricate anatomical deformities, such as hip dysplasia and severe acetabular defects, or osteoarthritis due to trauma, preoperative planning can be difficult. In such instances, conventional implant templates may not be adequate and tailored surgical techniques, and specific implants must be used. THA in patients with advanced acetabular deformities (e.g., cystic changes, fragmented acetabular bone) requires careful planning. In a study, the preoperative simulation with rapid prototype (RP) models showed that, based on 3D CT scans, there was a significant increase in the accuracy of the implant positioning. The value of 3D modeling in more complex scenarios was confirmed, with the final acetabular components used being within 2mm of the prediction in 80.9% of cases (38).

Despite the clear benefits of digital templating and computer-assisted planning compared to traditional approaches, incorporating these technologies into direct clinical practice has been met with its challenges. Computer-aided design (CAD) planning was, in fact, compared with exact conventional X-ray interpretation, and it stated that CAD significantly increased accuracy in the selection of implants. Less time for the operation, blood loss, and lesser hospital stay were factors that improved. Yet, despite these advantages, the widespread adoption of CAD and digital planning is limited primarily by economic barriers and software accessibility (24). Customized implants and 3D printing technologies could provide potential solutions for complex hip reconstructions; however, their cost and lack of accessibility still limit their use. The next challenge will be determining how to implement such advanced tools into routine preoperative workflows without substantially increasing healthcare costs (39).

Even though preoperative planning techniques have advanced, many challenges still interfere with accuracy, reliability, and clinical outcomes. Multiple limitations like standardization, magnification errors, and pelvic positioning hinder its accuracy for templating on radiographs. On the other hand, problems in implant sizing and intraoperative variations signal a need for better planning methods (21,37).

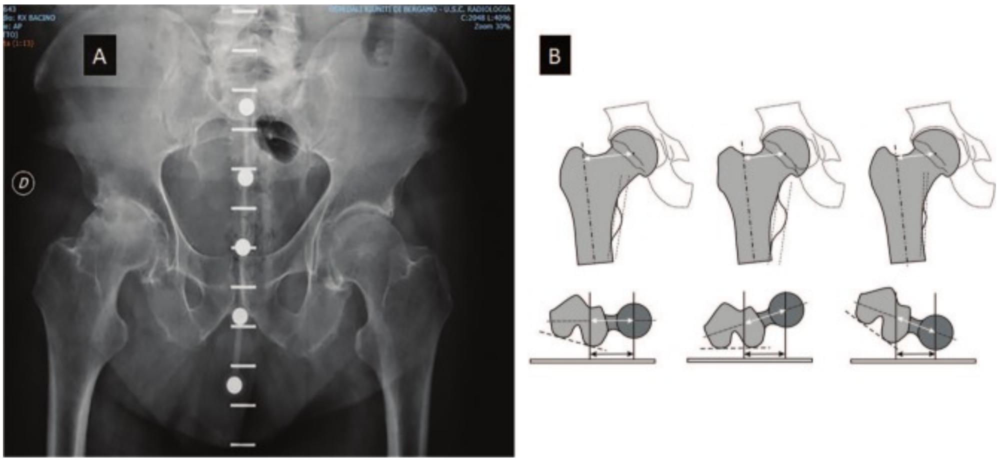

Figure 4 (a) Example of suboptimal radiograph due to incorrect femoral rotation and pelvic misalignment. (b) Impact of femoral rotation on offset evaluation

3.3.2 IMPACT OF INACCURACIES ON SURGICAL OUTCOMES AND REVISIONS

Mistakes in preoperative planning have serious consequences, especially implant mispositioning, which continues to be a leading cause of mechanical failure in THA (19). Misalignment subsequently leads to components faster wear off, instability, and additional stresses on nearby tissues. These factors can potentially contribute to implant loosening and early failure (19,21).

The risk for dislocation has been shown to be significantly affected by component orientation, soft-tissue balance, and restoration of hip biomechanics. Studies highlight that the precise implant position can reduce the risk of dislocation by achieving optimal femoral head size, cup inclination and combined femoral and acetabular anteversion (21). Correct planning minimizes the risk of impingement and secondary instability of the prosthesis which are key factors that, if neglected, can lead to dislocations and recurrent interventions (26).

Improper prosthetic fit due to inaccurate preoperative planning not only leads to poor implant longevity but also affects function postoperatively. Abnormal gait patterns, muscular imbalances, and chronic hip pain can arise from limb-length discrepancies. Such conditions greatly diminish patient satisfaction and sometimes necessitate further corrective surgery to restore function (22). Poor planning of both femoral and acetabular components further results in asymmetric load distribution, thus risking implant loosening and periprosthetic fractures (24).

Errors in preoperative planning can also result in unanticipated surgical challenges requiring longer operative time as surgeons must compensate for unforeseen anatomy while operating. Extended surgical times not only elevate the likelihood of elevated blood loss and infection, but can translate to longer hospital stays, slower patient rehabilitation and higher overall costs to the health care system. As a result, preoperative planning must be performed accurately not only for the individual patient's health outcomes but because this also alters resource utilization at the level of the health system (24).

4. POSTOPERATIVE OUTCOMES IN HIP REPLACEMENT

4.1 DEFINING SUCCESS

4.1.1 CRITERIA FOR SUCCESSFUL OUTCOMES

The success of total hip arthroplasty (THA) is multilayered. It consists of pain relief, functional restoration, implant longevity, and patient satisfaction. The efficacy of the procedure can be defined by these criteria, ensuring the patient's long-term benefits.

Pain relief is one of the aims of THA for osteoarthritis and other degenerative joint disorders. Studies have shown that the advantages of hip arthroplasty are long-term, with 86% of patients reporting a clinical reduction in pain levels five years after surgery (40). In addition, clinical assessments with PROMs (patient-reported outcome measures) demonstrate that THA results in considerable improvement in the intensity of pain. The Hip Injury and Osteoarthritis Outcome Score (HOOS) and Western Ontario and McMaster Universities Arthritis Index (WOMAC) demonstrate that between 88-93% of patients attain minimal clinically important differences (MCID) in pain relief during the year after the procedure (41).

An increase in functional capacity is another important measure to evaluate the success of THA. The ability to go about their daily life without pain or discomfort is a key component. In one study, the mean improvement in WOMAC function scores was 41 points among 7,001 patients undergoing THA (41). In addition, larger femoral heads (e.g., 36 mm) correlated with better functional outcomes, especially in active patients, by lowering the risk of functional complications (42).

The longevity of the implant is one of the most critical factors affecting the long-term success of THA. Kaplan-Meier survival analysis shows a 14-year implant survival of 92.7%, highlighting the durability of modern prosthetic bearing surfaces. However, the longevity of an implant depends on factors like surgical techniques, implant designs, and patient-based factors like comorbidities and activity level. Although revision is uncommon, evidence shows that 5 years postoperatively 10% of patients experience either a complication or suboptimal function (43).

Patient-reported outcomes are also parameters to measure successful THA. Overall satisfaction is determined by a combination of pain relief, functional improvement, and psychological well-being. It has been reported that at one- or two years following surgery, 66.8% and 76.5% of patients report successful outcomes based on pain control, function, and quality of life (44). Apart from clinical measures, patients' expectations also significantly affect their satisfaction. Previous research indicates a positive relationship between preoperative expectations and postoperative outcomes, advocating that informed patient education can improve overall satisfaction and recovery experiences (45).

4.1.2 METHODS FOR EVALUATING OUTCOMES

The assessment of outcomes in THA has undergone considerable changes over the years. Historically, outcome assessment was based on classic clinical metrics such as mortality, reoperation rates, implant success, and radiographic findings. However, there is increasing focus on patient-centered outcomes that measure functional recovery and quality of life after surgery. There are five important classes of outcome measurement: general health-related quality of life (HRQoL), activities of daily living (ADLs), mobility and physical function, disease-specific scales and joint-specific scales. Evaluators are suggested to utilize assessment tools from more than one category (46).

The use of PROMs (patient-reported outcome measures) has been widely adopted as a successful measure in evaluating hip replacements. PROMs are collected by the American Joint Replacement Registry (AJRR) both preoperatively and one year postoperatively. Some of the most used PROMs are Western Ontario and McMaster Universities Arthritis Index (WOMAC), Hip Injury and Osteoarthritis Outcome Score (HOOS) and HOOS for Joint Replacement (HOOS, JR). These metrics offer insights into pain relief, functional recovery, and patient satisfaction (41).

One debate concerning PROMs usage is the preference for single-question versus multi-item questionnaires. Modified Single Assessment Numerical Evaluation (M-SANE) is a single-item PROM that asks patients to rate their hip function from 0 to 10. Research comparing M-SANE to traditional PROMs suggests that M-SANE offers similar reliability and responsiveness with less patient effort (47).

Utilization of predictive models in the evaluation of THA outcomes is a relatively new area of interest. Machine learning models are trained on large-scale PROM datasets to predict patient outcomes with greater accuracy (48). This shows the opportunity for artificial intelligence to enhance the prediction of outcomes following surgery. Traditional outcome risk assessment using clinician judgment and patient history can only provide a limited picture; with machine learning algorithms, a broader spectrum of factors, including preoperative PROM scores, demographic information, and surgical factors, can be used to develop a risk profile (49).

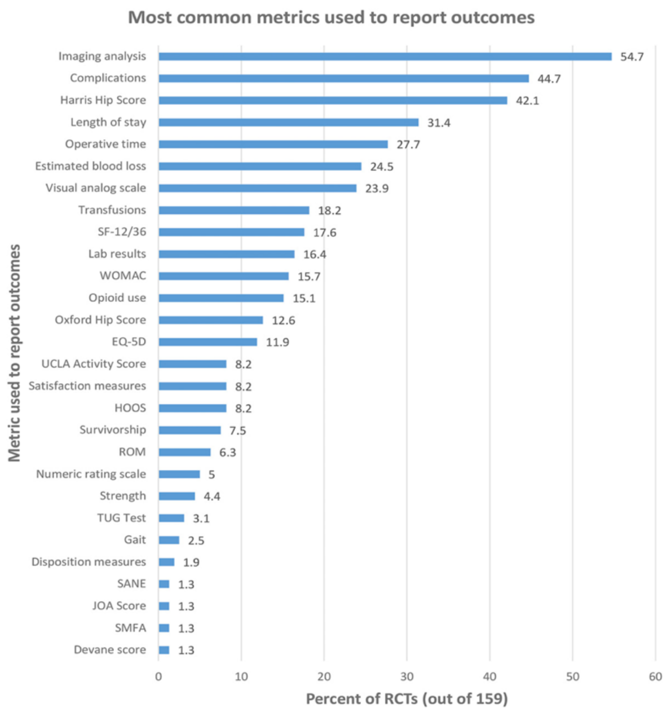

Figure 5 Most frequently reported outcome metrics on THA

4.2 COMMON POSTOPERATIVE COMPLICATIONS

4.2.1 LIST AND FREQUENCY OF TYPICAL COMPLICATIONS

Like any other surgical procedure, total hip arthroplasty comes with some potential complications.

Infection: Infections after THA can vary from superficial wound infections to deep periprosthetic joint infections, which have a more difficult treatment course. The prevalence is reported to be approximately 1-2% of cases, commonly due to associated risk factors including older age, obesity, diabetes, and extended surgical duration (50).

Dislocation: Dislocation is a common complication of THA, especially during the early postoperative phase. It happens in 1-3% of primary hip replacements but may be far higher in revision. Examples of patient-related risk factors could be neuromuscular disorders, weak abductor muscles, and not following postoperative restrictions (51).

Thromboembolic Events: Deep vein thrombosis (DVT) and pulmonary embolism (PE) are the most dreaded complications after total hip arthroplasty (THA). Thromboembolic complications have been reported in about 3.5% of cases and pulmonary embolism in 1.8%. Common risk factors are prolonged immobility, older age, obesity, and pre-existing cardiovascular conditions (51).

Cardiac Complications: Cardiac events such as acute myocardial infarction and arrhythmias are observed in 3.3% of patients after hip replacement surgery. Patients at increased risk are those with a history of cardiovascular disease, obesity, and advanced age. Longer duration of anesthetic has been particularly associated with a greater incidence of this complication (51).

Pneumonia: About 12% of patients undergoing surgery develop postoperative pneumonia, and the incidence is higher among the elderly, per usual. Better-preserved preoperative muscle mass and nutritional condition may be associated with lower postoperative pulmonary complications (50).

Periprosthetic Fractures of the Femur: One of the most significant complications of both primary and revision THA, is periprosthetic femoral fractures (PPFF). The incidence varies widely between 0.07% and 18%, and intraoperative fractures are more frequent on cementless stem placement. Individual risk factors are osteoporosis, female sex, rheumatoid arthritis, history of hip surgery, and falling postoperatively (52).

Nerve Disturbances: Somatic nerve complications such as lateral femoral cutaneous nerve palsies and pudendal nerve neurapraxias are found in up to 16.5% of cases. Although most nerve injuries recover in six months, a significant number of patients experience chronic sensory deficits (53).

Delirium: Postoperative delirium (POD) is a common but frequently undiagnosed complication after every surgery, affecting 12–51% of elderly individuals (54).

4.2.2 FACTORS INFLUENCING THE RISK OF COMPLICATIONS

As mentioned before, a few complications in the postoperative course can occur. These are driven by preoperative and patient-specific factors. It is important to know these risk factors, to improve the outcome of patients.

Obesity and Malnutrition: Obesity is a widely acknowledged risk factor in orthopedic surgery, above all in THA. Even though there is an association with early osteoarthritis (that is requiring hip replacement at an earlier age), its role in perioperative and postoperative complications is still debated. Research suggests that patients with a BMI >40 undergo primary THA nearly seven years younger than patients with a BMI <30. Others show higher rates of wound drainage, deep vein thrombosis (DVT), and surgical site infections (55). Hypoalbuminemia, a measure of malnutrition, is a stronger predictor of postoperative complications than obesity itself. Obese level III (BMI >40) patients have almost double the incidence of malnutrition, increasing the risk of respiratory complications, blood transfusions, and greater length of hospital stay (56).

Coagulation Abnormalities: Primary THA in patients with impaired clotting parameters is associated with a significant risk for excess bleeding and prolonged healing of tissue, along with an increased need for revision (57).

Sarcopenia: Patients with sarcopenia (defined as the decrease of muscle mass seen with age) also have delayed functional recovery and a higher risk of complications such as pneumonia or frailty-related morbidity. The Sarcopenia Index (SI) is a sensitive, cost-effective marker of muscle mass in hospitalized patients. Studies have examined the importance of the standard deviation of SI values on the rate of postoperative pneumonia in patients undergoing joint replacement (50).

Cardiac and Functional Status: It is well established that patients classified as ASA II are at significantly increased risk for adverse cardiac, pulmonary, and systemic inflammatory responses to surgery. Furthermore, poor preoperative functional status almost triples the risk of complications (58).

Preoperative Depression: Although much research on complications after THA has focused on physical health, the importance of mental health, especially depression, can't be missed. Impacts of preoperative depression include increases in hospital length of stay and worse functional outcomes (59).

4.3 ROLE OF POSTOPERATIVE ASSESSMENT

4.3.1 IMPORTANCE OF FOLLOW-UP RADIOLOGY

Radiology in the postoperative context in the follow-up of hip replacements is undeniable. This first image confirms that the implant is in its correct position and directs future radiographs. It should be intraoperatively, so in the worst case immediate intervention can be done. Repeated imaging over time helps detect signs of implant migration, damaging wear, as well as loosening, which can all lead to early failure. Imaging can determine if an implant is integrated correctly into the surrounding bone, which is especially important in less cemented prostheses, where bone ingrowth into the implant is important for long-term stability. Identifying any discrepancies early enables timely intervention that can help prevent costly and complex revision surgeries (60).

The orientation of the acetabular and femoral components is very important in determining the long-term success of THA, especially cup inclination and anteversion. Mispositioning may lead to edge-loading, increased wear, implant loosening, and dislocation, which is one of the most common indications for revision (61).

The use of follow-up radiographs is essential in the detection of complications such as periprosthetic fractures, osteolysis, and infection. Fractures that develop early due to stress shielding, or improper loading, can be seen on X-rays well before symptoms appear (60,62). Radiographs are also useful in spotting wear-related problems. Polyethylene wear produces particles that can cause osteolysis and bone loss that often go undetected until late (62).

AI and machine learning are slowly being used in radiographic evaluation. These systems can analyze data more rapidly and accurately than humans, as well as predict dislocation or loosening risks. While these technologies are still in their beginnings, they offer the potential for more precision and superior outcomes in the long term (63,64).

5. EFFECTIVENESS OF RADIOLOGIC TEMPLATING

5.1 ACCURACY AND PREDICTABILITY

5.1.1 STUDIES EVALUATING THE PRECISION OF RADIOLOGIC TEMPLATING

Studies have compared the accuracy of 2D and 3D templating to predict implant sizes. Schiffner et al. showed that 3D templating was notably superior to 2D templates in predicting stem and cup size and considered that CT planning could enhance preoperative planning (65). Sariali et al. also showed that CT-based 3D templating achieved higher accuracy when compared to traditional 2D techniques, though they did not formally state statistical significance (65). Viceconti et al. demonstrated that 3D templating is more accurate compared to both 2D templating and standard templating for acetabular cup selection, but this study also concluded that there is limited validation for this data (65). Moreover, Zeng et al. highlighted the benefit of 3D templating for patients with deformed femoral or acetabular anatomy when 2D templating may not be sufficient (65).

Digital Templating: Replacing analog templating with digital templating has increased the quality and quantity of preoperative planning. Another study comparing digital templating to a hybrid method (acetate templates placed over digital images) reported that the fully digital method significantly outperformed the hybrid method regarding the prediction of femoral stem size to ±1 size (93.8% versus 84.1%, $p = 0.032$), and femoral offset (90.3% versus 75.2%, $p = 0.004$) (66). Also, comparisons of 2D digital templating software (TraumaCad) and 3D digital templating software (hipEOS) show that reliability was great for both methods. 3D templating showed a significant advantage for short-stem femoral implants, specifically in estimating the appropriate stem size ($p = 0.029$) (67). However, no meaningful differences were identified for conventional straight-stem implants or acetabular cups (0.935 and 0.954, respectively) (67). This indicates that although digital templating enhances overall planning efficiency, its greatest advantages may be in special types of implants. In another study, researchers compared the use of digital versus acetate-based onlay templating and found that digital templating had better reliability. They achieved femoral stem accuracy at 85% and acetabular cups at 80%. In contrast, onlay templating only achieved 60% for acetabular components (68).

Callibration Methods: An accurate calibration of radiographs is critical for successful templating, as errors with magnification can result in incorrect estimations of implant sizes. The most common method is external calibration markers (ECM), but their accuracy is commonly affected by patient positioning and differences in marker placement. One revealing study observed discrepancies in a magnification factor of up to 23.3% with ECM use (69). To overcome these problems, a new dual-scale single marker (DSSM) approach was proposed. Using this, the absolute relative deviation was lower than those evaluated by ECM ($p < 0.001$). In addition, the overall performance of DSSM calibration was not affected by patient BMI, but the ECM errors increased with overweight and obesity (69). In another study comparing DSSM, ECM, and fixed calibration factors (FCF) on supine radiographs, it was found that DSSM provided the best accuracy, with the mean difference in absolute calibration factors reduced to 0.011 versus 0.105 for ECM ($p < 0.001$) (31).

Hybrid templating: Fusing digital and traditional approaches; hybrid templating methods have also been tested for accuracy. It was demonstrated that predictions of femoral stem size using the hybrid method were highly correlated to the final implanted size (ICC = 0.85), while acetabular prediction was less accurate (ICC = 0.45) (70). One study showed a match of the templated femoral implant size with the actual size in 65.2% of cases when using digital templating and the KingMark calibration device; this figure increased to 97.2% when a one-size difference was considered. For acetabular cups, the exact match rate is 46.3%, increased to 87.5% within 1 size (71).

Discrepancies: Although templating has improved, discrepancies exist between anticipated versus implanted sizes. According to a CT-based templating study, implant size agreement rates were 94.4% for acetabular cups and 85.5% for femoral stems. Consistent with this finding, significant differences in size mismatches were observed in both the coronal and sagittal planes, suggesting that adjustments within the intraoperative space may be needed even when templating predicts an ideal fit (72).

The experience of the surgeon also factors into templating accuracy. A study showed that the most experienced surgeons had the best ability to predict femoral as well as acetabular component sizes when using the MediCad digital software for preoperative planning. Rates were considerably lower for less experienced surgeons (67).

5.2 IMPACT ON OUTCOMES

5.2.1 IMPACT OF ACCURATE TEMPLATING ON POSTOPERATIVE RESULTS

Size prediction and postoperative fit: Of many factors, one of the most important is that the selected implant size closely approximates the anatomic proportions of the patient. A properly fitting implant decreases the occurrence of intraoperative complications such as periprosthetic fractures, and excessive bone resection during surgery, while also enhancing the long-term stability of the prosthesis (73). Templating in avoiding intraoperative complications is especially significant in cementless implants, where fitting is critical for stability. Because cementless femoral stems depend on press-fit fixation, inappropriate sizing can result in both fracture and suboptimal fixation, raising the potential for early implant failure. Intraoperative fractures have been demonstrated to occur more with cementless implants (1.5%–27.8%), and in some cases undersizing the femoral component to minimize fracture risk is indicated (74).

Leg Length Discrepancy: Templating helps in restoring leg length, and inaccurate restoration can lead to gait disturbances, instability, back pain, and increased risk of dislocation. Studies have shown that templating corrected leg length to ±5 mm in 54% of patients and to ±10 mm in 85%. In 15% of patients, it remained greater than 10 mm (75). Another showed a significant correlation between preferred and executed corrections, validating the use of templating to restore symmetry and thereby minimizing postoperative pain (76).

Stability and implant longevity: The appropriate orientation of a component minimizes dislocation and wear and increases the lifespan of the implants. Preoperative templating facilitates accurate positioning of femoral and acetabular components, as well as leg length discrepancy correction, which could be confirmed by radiographic imaging in the postoperative period (77). While mispositioned components may accelerate wear, promote instability, or lead to damage to the glenoid, templating has been shown to allow for < 10 mm LLD in 93.5% of cases, and optimal cup inclination in 88% (74). Moreover, surgical planning aids in the correct reconstruction of femoral offset, which is important for normal joint biomechanics and minimizing mechanical failure (76).

Role of advanced templating techniques: Novel 3D templating technologies may provide greater accuracy with 3D than 2D methods, particularly for high-demand short-stem designs that require precise metaphyseal fixation. According to one study, 3D methods were more consistent in regards to predicting the size of components and positioning with components (67). Alternatives like EOS biplanar imaging have also shown high-quality accuracy of implant planning with significantly less radiation exposure compared to CT-based methods (65).

5.2.2 RELATION BETWEEN TEMPLATING ACCURACY AND COMPLICATION RATES

As already mentioned, periprosthetic fracture is one of the major consequences that could be affected by templating mistakes. If a stem is too large, this may require over-reaming of the femoral canal, thus weakening the bone and increasing the risk of femoral fracture. Alternatively, an undersized stem may lead to instability with an intraoperative adjustment that can also predispose for fractures (67).

Dislocation risk is another prominent issue in THA and is often closely correlated with component position. Data shows that the accuracy of component implant position can significantly reduce dislocation rates. Inaccurate templating may lead to mispositioning and has been associated with an increased risk of failure post-operatively, and the need for revision surgery (65).

Aseptic loosening, one of the causes of both implant failure and revision THA, is also a complication that can be influenced by the accuracy of templating. The lack of passive stability on the implant-bone interface leads to micromotion that can impair osseointegration and foster loosening (78).

Limb length discrepancy (LLD) is an important issue following THA since even minor differences in leg lengths may result in altered biomechanics, gait disturbances, or lower back pain. Preoperative templating assists in more accurate calculations of leg length restoration by considering the patient’s natural anatomy (79).

In addition to individual complications, templating accuracy has been shown to decrease both total surgical time and revision rates. By having implant sizes and positions predefined with high fidelity, surgeons can execute more efficiently and eliminate many intraoperative steps that allow for first- and second-change components. Finally, more accurate templating minimizes the number of early revisions, resulting from implant malalignment or instability with favorable long-term outcomes and reduced healthcare costs (68).

5.3 ADVANCES AND INNOVATIONS

5.3.1 DESCRIPTION OF NEW TECHNOLOGIES AND SOFTWARE IN TEMPLATING

AI-based planning software: AI is a powerful tool and can greatly improve efficiency and accuracy in preoperative planning for THA. AI HIP is an AI-based planning software that utilizes deep learning models to predict optimal prosthesis sizes and automatically recognize acetabular and femoral morphology. It avoids manual template positioning, which helps to reduce subjectivity and ensures the standardized selection of implants. A recent study assessing AI HIP reported that it achieved an accuracy of 74.58% for acetabular cup prediction and 71.19% for femoral stem prediction, outperforming 2D templating which yielded 40.68% and 49.15% accuracy for acetabular and femoral components. Secondly, AI HIP was at least an order of magnitude faster than 3D templating software, which took over half an hour for a single case as opposed to just under four minutes for AI HIP per case. However, accuracy was lower with cases like developmental dysplasia of the hip; requiring for more AI training (80).

Deep learning and computer vision: Deep learning-based planning is another promising innovation in THA. To achieve that level of accuracy, AI algorithms can segment anatomical structures on radiographic images and predict the ideal size of each component, as well as its position. In a study, deep learning models predicted acetabular and femoral component sizes with an accuracy of 78.9% and 70.9%, which were near that of human experts (81).

Mobile technology with PACS: Mobile-based templating solutions have seen a rapid uptake in resource-limited environments. It was found that a novel templating method, utilizing an iPhone and Keynote software, was able to accurately predict the femoral stem size in 93.8% of cases (within one size), and significantly outperformed the traditional hybrid method (84.1%). In both techniques, the prediction of the acetabular cup was accurate in 92.9% vs. 89.4% (66).

3D digital templating: A study evaluating 3D templating versus conventional 2D, revealed that although 3D templating provided improved prediction, 2D templating (digital means) did not significantly differ. 3D methods, however, allowed for superior visualization of femoral torsion and offset, which are important influences in achieving optimal joint biomechanics (67).

Digital templating software. Some well-known examples are TraumaCad and MediCAD, providing high accuracy in predicting the size of components. Advantages include a standard and reproducible method with less interobserver variability. Moreover, electronic storage of pre-operative images makes it easy to analyze post-operative outcomes and plan for future surgery (82).

5.3.2 POTENTIAL FOR FUTURE IMPROVEMENTS

With the introduction of more anatomical diversity, including pathologies like acetabular dysplasia, AI-based planning software can continuously improve and lead to better implant selection and fewer complications (66). These tools could be combined with low-dose biplanar radiography and other 3D imaging techniques, giving high-quality detail on anatomy with limited ionization, particularly useful in short-stem prostheses that rely upon precise metaphyseal fixation (67).

Deep learning could automate the detection of anatomical landmarks and improve the accuracy and reproducibility of implant sizing and positioning. Also, computer vision provides an opportunity for intraoperative feedback in real time and immediate feedback from live imaging can improve component positioning and reduce uncertainty (83).

Many mobile templating tools could benefit low-resource settings once interfaces become more efficient and calibration accuracy improves. Improved mobile image quality would additionally aid in better implant predictions (84,85).

3D templating improves upon 2D and may prove even more accurate as algorithms change to minimize position- and magnification-associated errors (65,67). These tools are of value in complex deformities, in which improved hip center reconstruction and more sophisticated calibration techniques could improve the outcomes and reproducibility (65,68).

6. IMPLICATIONS FOR CLINICAL PRACTICE

6.1 ADOPTION OF ADVANCED TEMPLATING TECHNIQUES

6.1.1 3D IMAGING AND COMPUTER-AIDED DESIGN

The incorporation of 3D imaging and computer-aided design (CAD) into preoperative planning has improved accuracy in determining the size and alignment of an implant placed in THA, thereby improving outcomes and minimizing the possibility of complications like instability, wear, and limb length discrepancy (24). CAD-based reconstructions give precise views of complex hip anatomy and help select devices and osteotomy sites, especially in difficult cases (24).

Advances such as EOS biplanar imaging provide accurate 3D assessments with significantly reduced radiation exposure and facilitate planning for short-stem prostheses and the evaluation of functional parameters such as femoral offset and torsion (67). AI HIP is an example of an AI-based 3D templating tool that reduces planning time and achieves high accuracy by automatically identifying main anatomical regions (80).

More sophisticated systems such as HIP-PLAN or Zed Hip perform exact biomechanical reconstruction with the aim of improving surgical precision and decreasing inconvenience, but the long-term benefits are still under investigation (28). These technologies are particularly useful for inexperienced surgeons, facilitating surgical planning and reducing the risk of complications, such as periprosthetic fractures (86).

New features, such as 3D software based on activity simulations, might also allow the ideal orientation of an implant to help prevent impingement and dislocation during dynamic movement, and even improve postoperative satisfaction (87).

6.1.2 TRAINING FOR SURGEONS AND RADIOLOGISTS

Increased adoption of advanced templating systems in THA must be accompanied by strategies for targeted training.

Programs need to focus on the importance of proper magnification correction, as relatively minor errors (6%) can have a significant impact on implant sizing. The training should include marker placement (e.g., metal coins on ASIS) and calibration accuracy (88).

Surgeons need to familiarize themselves with EOS imaging that provides precision measurement due to reduced magnification errors with full-limb, weight-bearing images. Training must encompass the interpretation of EOS scans and evaluation of leg length discrepancy and femoral offset (89).

AI software education is important to facilitate templating, especially in advanced anatomies. Training should include navigation of automatic segmentation, marker recognition, and optimal prosthesis choice in challenging patients (80).

The importance of precision must be stressed and correlated with a reduction in complications such as fractures, loosening, and dislocation (90). Last, programs should involve continuous updates, practical workshops, and feedback mechanisms to ensure surgeon competence as technology matures (67,89).

6.1.3 STANDARDIZED PROTOCOLS

Uniform preoperative planning allows for accurate implant size prediction, reduces inter-surgeon and inter-institution variability, and promotes constructive comparison of outcomes (88,89).

The accuracy of templating is also known to vary, with most of the digital methods reaching accuracy levels of 76% for cemented and 72.5% for cementless prostheses (88). Magnification correction alone using known-size markers can greatly increase precision. There is still a large potential for error if markers are not used consistently, suggesting the need for standardization in calibration procedures (88,90).

Standardization is also needed for outcome reporting. Due to the variability in defining acceptable templating margins (e.g., ±1 implant size), the clinical assessment is inconsistent. Agreement on clear accuracy thresholds – let's say, of ±1 size for stems and ±2 mm for acetabular components – would enable more meaningful comparisons between studies (88–90).

Standardized reporting would also facilitate the assessment of evolving tools such as HIP-PLAN, AI HIP, and Zed Hip (80,89).

Unified protocols in templating and clinical and radiographic outcome assessments are necessary to provide high-quality patient care during and after the intervention.

7. CONCLUSION

7.1 SUMMARY OF KEY FINDINGS

This literature review examined how radiological planning in THA can be improved and what that accuracy means. The findings underline that success with hip replacement doesn't start in the operating room; it starts in the planning process. Precise preoperative planning facilitates ideal prosthetic choice with good limb length restoration and alignment of components. These factors directly impact stability, mobility and long-term prognosis of patients with THA (19,22, 24).

This process hinges on radiologic templating. When templating is done right it can serve as a good connection between diagnostic imaging and surgical action. However, many traditional calibration techniques, especially those that involve external markers, remain susceptible to error. It was pointed out that even minor errors in the correction applied for magnification can lead to statistically relevant errors in implant size or position. Thus, increasing the risk of complications such as dislocation, limb length discrepancy, or loosening [31,33,34]. Recent methods such as the dual scale single marker (DSSM), EOS imaging, and AI templating systems show great promise as an answer to the risk with some current methods and have better reliability (31,67,80).

The outcomes following surgery are a mirror of the quality of the planning and templating procedure. Long-term results are influenced by accurate positioning of implant, restoration of biomechanics, and early diagnostics of mechanisms of complications (studies by imaging and PROMs). Studies have found that patients whose procedures were performed according to detailed planning generally experience fewer complications, have faster recoveries, and greater degrees of satisfaction (41,60,62,75).

Accurate radiologic planning is described as an essential element of successful THA in the literature. Evidence suggests it enhances surgical accuracy, diminishes complication rates, and fosters long-term implant viability. Finally and most importantly favoring both patients and the healthcare system (24,65,68).

7.2 VISION FOR THE FUTURE

To sum up, hip arthroplasty has the widest potential for improvement in this area, provided that the appropriate technologies and practices are utilized moving forward. THA is a well-rounded procedure and has persevered for ages. Still, there is always room for improvement, especially in a day and age where innovations are launched left and right. A clear priority is further broadening the use of advanced calibration and templating approaches. DSSM, EOS imaging, and AI-enabled instruments are already more accurate and more consistent than many traditional approaches. Adopting these into daily practice might reduce human errors and simplify planning in clinical settings (31,67,80).

Concurrently, standardized protocols on patient position, marker location, and outcomes should be established. Without a defined path, the most sophisticated software solution or imaging system will continue to produce inconsistent results. Standardization of calibration processes and outcome benchmarks will enable clinics to regulate their performance and to improve via data rather than trial-and-error (88–90).

Training and ongoing education have to keep up with these technical advances, too. Surgeons must be confident in using new software and imaging systems, particularly those that use AI or 3D software. Structured programs and hands-on training will be needed, not merely to learn the tools, but to know when to trust them, when to question them, and how to apply them to complex or unusual cases (80,89).

Over time, more accurate radiologic planning can ultimately lead to fewer revision surgeries, lower healthcare costs, and improved patient quality of life. And while THA becomes more common globally, even slight improvements to planning accuracy will realize a significant impact. Patients will see improved outcomes, surgeons will operate with greater finesse and efficiency, and healthcare systems will experience fewer unnecessary complications.

What this review ultimately reveals is that improving radiologic planning isn't simply about better imaging or smarter software, it's about establishing a more accurate, uniform, and patient-centered approach to the "Operation of the Century" (1). The tools already exist. The real challenge now is not only successfully putting them into practice, and training teams on how to use them well, but in keeping the process dynamic to improve the benefit to every patient undergoing THA.

8. RESOURCES

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LIST OF FIGURES

Figure 1 Comparison of 3D anatomical models

Mandolini M, Brunzini A, Facco G, Mazzoli A, Forcellese A, Gigante A. Comparison of Three 3D Segmentation Software Tools for Hip Surgical Planning. Sensors (Basel). 2022 Jul 13;22(14):5242. doi: 10.3390/s22145242. PMID: 35890923; PMCID: PMC9323631.

Figure 2 Positioning of DSSM (unfilled circle) and standard ECM (filled circle) marker in supine radiograph setup

Loweg L, Trost M, Kutzner K, Ries C, Boese C. A novel calibration method for digital templating of total hip arthroplasty: a prospective clinical study of dual scale type single marker calibration in supine radiographs. Int Orthop. 2020;44:1693–9. Placement of anterior

Figure 3 Anteroposterior pelvic radiograph showing left-sided short stem THA, DSSM (1), prosthesis head component (2), and standard ECM (3) in supine position

Loweg L, Trost M, Kutzner K, Ries C, Boese C. A novel calibration method for digital templating of total hip arthroplasty: a prospective clinical study of dual scale type single marker calibration in supine radiographs. Int Orthop. 2020;44:1693–9. Placement of anterior

Figure 4 (a) Example of suboptimal radiograph due to incorrect femoral rotation and pelvic misalignment. (b) Impact of femoral rotation on offset evaluation

Colombi A, Schena D, Castelli CC. Total hip arthroplasty planning. EFORT Open Rev. 2019 Nov 1;4(11):626–32.

Figure 5 Most frequently reported outcome metrics on THA

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