GMR
The Original

PATIENT-SPECIFIC BIOMECHANICAL MODELING FOR OPTIMIZING IMPLANT ALIGNMENT AND LONGEVITY IN TOTAL HIP ARTHROPLASTY

[*1]Vrushabh U Kumbhare, [2]Dr Sudhira kumar Padhan, [3]Dr. Sheetal Sharma, [4]Dr. Anuj Prasad, [5]Dr Tushar Ranjan Dalei

[*1]Jawaharlal Nehru Medical Collage, Sawangi, Datta Meghe Institute of Higher education and reasearch , Sawangi, M. S. Orthopedics, Department Orthopedics, Email ID:vrushu.uk@gmail.com, Orcid ID:https://orcid.org/0000-0002-8987-856X
[2]MBBS, MS Orthopedics , Assistant professor, Department of Orthopaedic, VIMSAR ,Burla, Sambalpur, Odisha, Email ID: sudhirapadhan2@gmail.com
[3]Senior Resident, Department of Orthopedics, Guru Gobind Singh Indraprastha University, Delhi, ORCID ID: 0009-0007-1966-9432, Email ID: sheetalanilsharma@gmail.com
[4]Senior Resident, Department of Orthopaedics, Guru Gobind Singh Indraprastha University, Delhi. ORCID ID: 0009-0004-6196-6199, Email ID: divergent1005anuj@gmail.com
[5]Associate Professor, Vimsar, Burla, Sambalpur, Department Of Orthopaedic, Email ID: tusharranjan3009@gmail.com

ABSTRACT:
Background: Total hip arthroplasty (THA) is a highly effective procedure for relieving pain and restoring mobility in patients with advanced hip disease, but implant longevity remains influenced by alignment accuracy, bone quality, joint loading, soft-tissue balance, wear, instability, and patient-specific anatomical variation. Conventional implant positioning strategies often rely on generalized alignment targets and static radiographic parameters, which may not fully account for differences in femoral offset, acetabular version, pelvic tilt, spinopelvic mobility, gait mechanics, and functional activity. Patient-specific biomechanical modeling offers a precision-based approach for optimizing implant alignment by integrating imaging-based reconstruction, finite element analysis, musculoskeletal simulation, wear prediction, and functional assessment of hip-spine mechanics. These models can support individualized prediction of stress distribution, implant fixation, impingement risk, joint loading, edge loading, and postoperative instability. Robotic-assisted surgery, navigation-guided systems, artificial intelligence, digital twins, and three-dimensional printing may further enhance the translation of computational planning into surgical execution. This review discusses the biomechanical principles, modeling techniques, clinical applications, limitations, and future directions of patient-specific biomechanical modeling in THA. Although broader clinical adoption requires standardized workflows, prospective validation, cost-effectiveness analysis, and long-term outcome data, individualized biomechanical planning may improve implant positioning, reduce mechanical complications, and support more durable precision arthroplasty.

KEYWORDS: Total hip arthroplasty, Patient-specific biomechanical modeling, Implant alignment, Spinopelvic mobility, Implant longevity

INTRODUCTION

The procedure of total hip arthroplasty (THA) is one of the best surgical techniques to relieve pain, restore function, and improve the quality of life in patients with a highly symptomatic hip disease, such as advanced degenerative, inflammatory, traumatic, and deformity-related hip disease. The technique has undergone significant changes as the materials used for the implants have improved, as have the bearing surfaces, fixation, peri-operative treatment, and the surgical technique. In spite of these developments, the long-term success of implants still relies on the combination of the implant design, host anatomy, implant alignment strategy, bone quality, soft-tissue balance, and loading. However, longevity of the implant is not only dependent on the properties of the material, but also on how the reconstructed hip has to cope with the forces when standing, walking, climbing stairs, and carrying out other normal activities. Modern selection of materials is thus closely associated with function, biomechanical compatibility, wear resistance, and fixation stability, as well as patient-specific functional requirements [1].

A key factor in the success and survival of a THA is implant alignment. Malposition of the acetabular or femoral component may change hip biomechanics, cause impingement, decrease range of motion, enhance the wear of the bearing surfaces, impair the function of the hip abductors, and increase the likelihood of hip instability or revision surgery. Previous methods have been based on the use of generic alignment goals, such as a predetermined range of acetabular inclination and anteversion. These strategies may be helpful for technical advice, but do not consider the variation in pelvic orientation, femoral morphology, spinal mobility, and dynamic change of posture within the individual. Recent publications have stressed the need to assess acetabular position in the context of the entire functional anatomy instead of focusing solely on the radiographic imaging [2].

Patient-specific planning has become a more important approach as no two hips are exactly alike. The postoperative mechanics can be significantly altered by variations in some of the following factors: anteversion of the femur, version of the acetabulum, pelvic tilt, limb length, femoral offset, bone stock, and muscle function. Patient-specific orthopaedic solutions aim to position implants in a patient’s body with respect to the patient's anatomy and functional needs rather than to fit a variety of patients with a similar implant positioning. It is especially applicable in developmental dysplasia, post-traumatic deformity, abnormal version of the femur, severe osteoarthritis, revision surgery, and complex arthroplasty [3].

Biomechanical modeling is a technique that can be used to convert anatomical and functional variability to clinically relevant planning information. The prediction of implant position effects on stress distribution, range of motion, fixation, wear, and risk of implant instability can be achieved by the use of imaging-based 3D reconstruction, finite element analysis, musculoskeletal simulation, gait-informed load estimation, and computational impingement analysis. The osteoarthritis itself leads to a number of compensatory biomechanical adaptations related to joint loading, gait asymmetry, muscle activation, and movement strategy, which could remain or develop following surgery. Patient-specific loading might provide a more effective ability to predict postoperative mechanical response [4] if these patterns are considered in planning the THA.

Further, with the development of technology, the potential of individualized biomechanical planning has increased. The three-dimensional printing, the custom manufacture of implants, the porous structures, and the concepts of regenerative implants have opened up new possibilities for the individual adaptation of implant geometry, surface architecture, and osseointegration potential to the individual anatomy [5]. The aim of positioning the implants personally has also been suggested to restore native joint kinematics closer to the mean values for the population than to the mechanical alignment methods, especially if the native joint kinematics does not match the population average [7]. These advances indicate a shift in the approach to planning THA from a parts-based approach to a biomechanical, patient-based approach.

Postoperative instability continues to be an important clinical issue, and its influence is related to component orientation, soft-tissue tension, surgical approach, head size, neuromusculature status, and patient-specific anatomy. Dislocation prevention is not just about an acceptable implant position but also about evaluating hip function after a hip reconstruction in the normal range of function and in the various postures [6]. The spinopelvic mechanics are particularly important as they can have a significant influence on the functional orientation of the pelvis in standing, sitting, and movement, which can affect the orientation of the cups. Therefore, patients with spinal deformity, fusion, sagittal imbalance, or limited spinopelvic mobility may need to have individualized implant targets to minimize the impingement and instability risk [8].

The recent concept of personalized arthroplasty is a justification for the use of the concept of personalized alignment, as well as implant selection and the execution of the surgery [9] to ensure better function and durability. This approach raises the question of whether the standardized positioning objectives are best for every patient and focuses on the elements of anatomy, biomechanics, activity demands, and functional goals [10]. In this context, patient-specific biomechanical modelling can be used as a link between pre-operative imaging, computational prediction, intra-operative execution, and implant performance in the long-term. In this review, we will explore how patient-specific biomechanical modeling can be used to optimize implant alignment and improve long-term implant survival in THA, highlighting the significance of variations in the anatomy, imaging reconstruction, finite element modeling, musculoskeletal simulation, spinopelvic mechanics, implant wear, TARS, clinical validation, and the future direction of patient-specific biomechanical modeling in THA.

Objectives of the review:

1. To evaluate the role of patient-specific biomechanical modeling in optimizing implant alignment in total hip arthroplasty.
2. To examine how anatomical variability, spinopelvic mobility, and joint loading influence implant stability and longevity.
3. To review current and emerging technologies that support personalized planning, simulation, and execution in total hip arthroplasty.

2. Biomechanical Principles of Total Hip Arthroplasty

Total hip arthroplasty (THA) aims to achieve a stable, mobile, and load-distributing reconstruction that will restore hip function as best as possible without creating undue stresses at the bone–implant interface. The coordinated relationship between the center of the femoral head, the orientation of the acetabulum, the femoral offset, the abductor lever arm, the length of the limb, capsuloligamentous restraint, and the dynamic action of the muscles is essential for a normal hip [11]. This can affect joint reaction forces, efficiency of gaiting, the tension of soft tissue, and affect implant stability. Anatomic restoration cannot be limited only to replacing damaged articular surfaces; it must be the mechanical environment that controls hip motion and load transfer that is restored [12].

The femoral offset is of great importance and is responsible for the abductor tension, hip stability, range of motion, and biomechanics of the limb. Failure to restore the offset adequately can have a negative effect on the abductor lever arm, create an increased limp, decrease soft-tissue tension, and increase the risk of instability. A large offset can result in an increase in trochanteric pain, soft tissue stretching, and implant loading. Therefore, offset planning must take into account stability, function, and patient-specific anatomy, not just targets for reconstruction in the general case of [11].

The alignment of the implants can also influence impingement-free motion and risk of implant dislocation. A narrow functional safe arc of motion, caused by component malposition, soft-tissue tension, and/or changes in the version of the femur and/or the restoration of the hip center, may predispose to instability after THA [13]. Patient-specific joint mechanics are tried to be restored by the use of personalized alignment concepts, which attempt to align components according to native joint orientation and anatomy, and also take into account the function and kinematics of the joints

[7]. The principles of biomechanics are the basis for patient-specific modelling in THA. The major biomechanical goals of THA are to align the implant, restore the hip mechanics, and return the offset to normal (Figure 1).

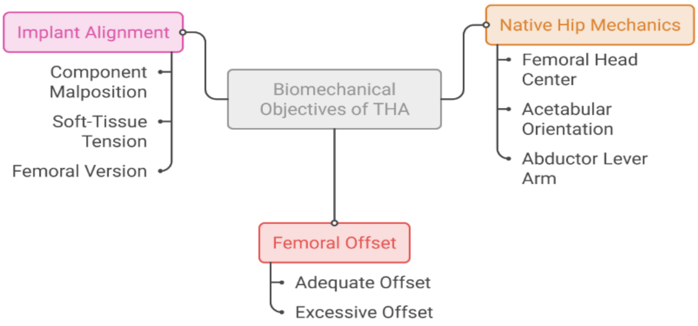

Figure 1. Biomechanical objectives of total hip arthroplasty: implant alignment, native hip mechanics, and femoral offset

3. Limitations of Conventional Implant Alignment Strategies

Traditionally, the positioning of the implant in THA has relied on the surgeon's visual estimation, mechanical guidance, anatomic landmarks, intraoperative judgement, as well as postoperative radiographic evaluation. Though these techniques are still commonly employed and, under the experienced hands, may yield accurate results, each of these factors can lead to a lack of accuracy: the positioning of the patient, the movement of the pelvis during surgery, exposure of soft tissue, obesity, anatomical deformity, and a surgeon's interpretation of the accuracy of the measurement. Manual techniques are also reliant on precise identification of the landmarks during surgery, which can be distorted when patients have dysplasia, osteophytes, previous surgery, severe osteoarthritis, or atypical pelvic shape [16].

One of the drawbacks of traditional alignment is that they use static acetabular cup targets. The traditional safe zone concepts give very general recommendations for cup inclination and anteversion and do not necessarily represent the functional orientation of the pelvis in standing, sitting, and during gait. A cup that looks good on a supine radiograph may not work as well in weight-bearing or if the patient has modified mobility at the spine-pelvic junction. Modern presentations thus stress the use of functional anatomy, pelvic tilt, femoral version, impingement risk, and stability requirements of the patient in the positioning of the acetabulum [2] instead of relying on the use of generalised angular values.

Technological comparisons also show that the manual alignment can only measure them to a certain extent. These include robot-assisted, computer-navigated, augmented reality-guided, patient-specific instrumentation and accelerometer-based systems that have been studied to increase the consistency of component placement and decrease outliers from the conventional systems [15]. Imageless navigation has also been suggested as a way of optimizing the placement of the acetabular component without having to utilize computed tomography in the preoperative planning phase, with issues of cost, workflow, registration accuracy, and learning curve also posing significant challenges [17]. The above restrictions justify patient-specific biomechanical modelling to help align beyond traditional static targets. As shown in Figure 2, conventional implant alignment has some restrictions, and the reason for the use of patient-specific biomechanical modeling is.

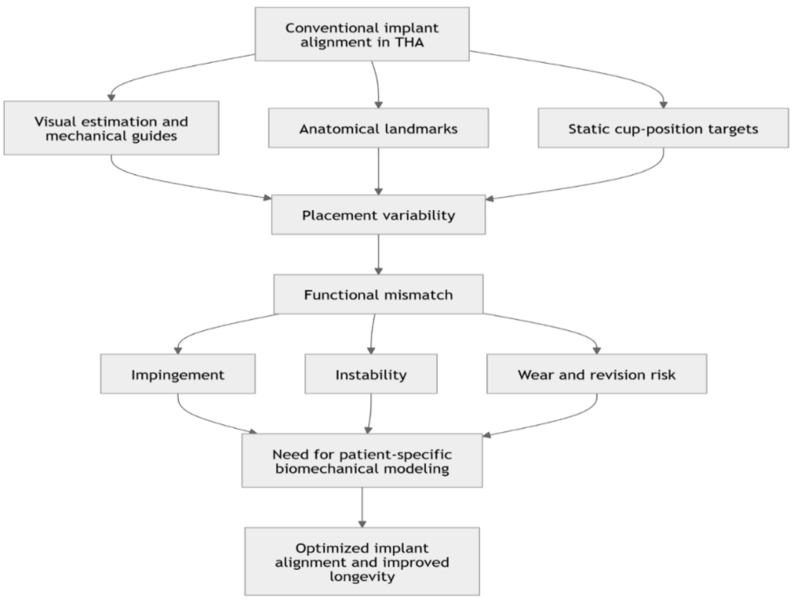

Figure 2. Limitations of conventional implant alignment and rationale for patient-specific biomechanical modeling in total hip arthroplasty

4. Patient-Specific Anatomical Variability in THA Planning

In total hip arthroplasty (THA), anatomical variability of the patient is one of the most important factors that affects implant positioning, mechanical reconstruction, and implant performance [18]. Traditional templates offer good approximations of the size of components, femoral offset, limb length, level of neck resection, and center of rotation, but today, more and more THA planning relies on three-dimensional analysis of the pelvis and femur. The depth of the acetabulum, the version, the geometry of the canal, the femoral offset, the presence or absence of a limb-length discrepancy, and the bone stock are all factors that can significantly influence implant selection and alignment. In the modern era, the approach to templating has moved away from just radiographic sizing and has become a more comprehensive process that takes into consideration anatomic variations, digital imaging, deformity correction, and intra-operative execution [19].

The clinical application of individualized anatomy in Robotic-assisted THA encompasses patient-specific imaging, component sizing, acetabular orientation, and intraoperative registration. This can enhance reproducibility but comes with the need to be cautious with exposure, identifying landmarks, registration, and how a virtual plan translates to the surgical field, as well as the limitations of this approach [20]. Developmental dysplasia, previous trauma, excessive osteophyte growth, and abnormal femoral version are all examples of abnormal anatomy that are particularly important when patient-specific planning is required.

Anatomical and functional variability of the hip–spine relationship is another. The functional acetabular orientation in static alignment during standing vs. sitting may differ due to pelvic tilt, lumbar stiffness, sagittal imbalance, and/or spinal fusion and may lead to impingement or instability if not adjusted for the particular position in question [21]. Advances in imaging can assist in the evaluation of spinopelvic mechanics, pelvic mobility, and risk of pelvic instability prior to surgery to aid in personalized THA [22]. All these reasons make patient-specific biomechanical modeling a valuable method for implant alignment for each patient. Table 1 lists some of the biomechanical and anatomical characteristics that will affect the alignment of implants in THA.

Table 1. Biomechanical and Anatomical Factors Influencing Implant Alignment in Total Hip Arthroplasty

Factor	Relevance to THA Planning	Biomechanical Implication	Modeling/Application Focus	Reference
Femoral offset	Guides restoration of the abductor lever arm and soft-tissue tension	Inadequate offset may reduce stability and gait efficiency	Offset reconstruction and implant selection	[11]
Native hip anatomy	Defines acetabular orientation, femoral geometry, and hip center	Altered anatomy affects load transfer and range of motion	Anatomical reconstruction and alignment planning	[12]
Instability risk	Influences cup position, femoral version, and soft-tissue balancing	Malposition may increase impingement and dislocation	Stability assessment and functional safe arc prediction	[13]
Personalized kinematics	Supports implant positioning based on patient-specific motion	Restores function beyond standardized mechanical targets	Kinematic alignment and individualized reconstruction	[14]
Hip-spine relationship	Determines functional acetabular orientation during posture change	Abnormal pelvic mobility may increase impingement risk	Standing-sitting assessment and cup target adjustment	[37]

5. Imaging-Based Reconstruction for Biomechanical Modeling

Patient-specific biomechanical modeling is fundamental for total hip arthroplasty (THA), and imaging-based reconstruction plays a vital role in it. While two-dimensional radiographs are important for diagnosing and templating a hip, they are of limited value when it comes to defining complex pelvic morphology, the version of the femur, the orientation of the acetabulum, bone defects, and three-dimensional deformity. Individualised implant sizing, orientation, and prediction of bony impingement are aided by three-dimensional (3D) reconstruction, which can be obtained from computed tomography (CT). Changes in the preparation and in real-time navigation during surgery are particularly important for accurate acetabular positioning and reconstruction of hip mechanics, and are increasingly using CT-based planning [23].

In hip and pelvic surgery, imaging reconstruction has been further expanded in the clinic by three-dimensional printing technology. The segmented imaging data can be transformed into physical models that help in understanding the complex anatomy, planning osteotomies, assessing bone loss, creating custom guides, and rehearsing technical and complex procedures. These applications are especially beneficial in revision THA, pelvic discontinuity, acetabular defects, dysplasia, tumor reconstruction, and complex deformity, in which it may be difficult to interpret the radiographs alone [24].

The accurate imaging reconstruction is also important for individual prosthesis design. Recent developments in the materials used to manufacture the three-dimensional-printed bone prostheses have enabled the use of customized implant geometry, porous structures, and more favorable integration potential of the implants into the bone, which has made it possible to achieve anatomical reconstruction in conjunction with biomechanical compatibility [25]. Three-dimensional planning allows for better interpretation of the inclination of the cup, anteversion, pelvic tilt, and functional orientation than does the use of static radiographic targets for acetabular alignment [2]. Imaging-based reconstruction is thus an anatomical basis for patient-specific simulation, navigation, and implant optimization in THA. The patient imaging, 3D reconstruction, implant planning, biomechanical modeling, and optimized alignment stages of the workflow are shown in Figure 3 as a sequence of imaging. The imaging-based workflow of patient imaging, 3D reconstruction, implant planning, biomechanical modeling, and optimized alignment is shown in Figure 3 as a sequence of imaging.

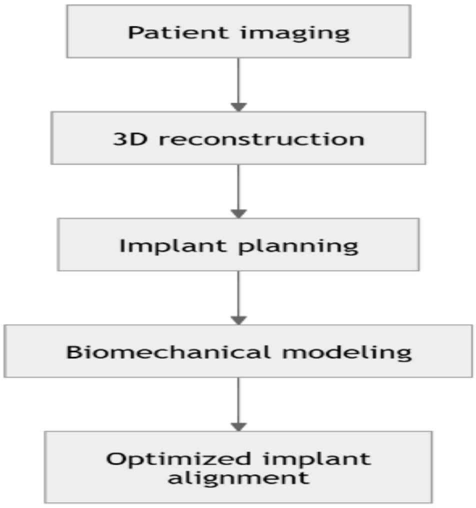

Figure 3. Imaging-based reconstruction workflow for patient-specific implant planning and biomechanical modeling in total hip arthroplasty

6. Finite Element Modeling for Implant Fixation and Bone Remodeling

The finite element method (FEM) is an important computational method that has been used in the field of total hip arthroplasty (THA) to assess fixation, stress transfer, and bone remodeling. FEA can approximate the distribution of forces within the patient-specific anatomical structures (femoral stem, acetabular cup, cement mantle, cortical bone, cancellous bone, and anatomical interfaces) by converting patient-specific anatomical data into numerical models. The simulations are especially relevant as these parameters - the success of the primary stability, avoidance of excessive micromotion, abnormal stress concentration, and progressive periprosthetic bone loss - are important factors in the survival of the implants. One of the major issues to be considered is stress shielding, which can lead to an underloading of the proximal femur, adaptive bone remodeling with loss of bone mass, and late failure (loosening or periprosthetic fracture) [27].

FE methods are also helpful in assessing the biomaterials and implant design before clinical use. In the virtual testing of mechanical properties, the stiffness, geometry of the surface, porous architecture, stem length, fixation method, and bearing properties can be tested under various loading cases. These models can be applied to the comparison of metals, ceramics, polymers, composites, coatings, as well as porous structures in terms of fatigue behaviour, wear resistance, stress distribution, and potential for osseointegration [28].

The design optimization of man-made hip prostheses has more and more relied on computational evaluation, rather than just empirical geometry. Finite element analysis can be used to locate high stress areas, to profile the implant to transfer load to the bone, and to predict the region of the body to which the load is transferred, and to modify the stem shape, neck geometry, cup thickness, and area of fixation. Such models can also include tissue differentiation and bone remodeling algorithms to model the bioadaptation of orthopedic implants over time [30]. Patient-specific finite element modelling is thus a mechanism-based aid to better align, fix, and sustain implants in the long term while improving THA survivability.

7. Musculoskeletal Modeling and Joint Loading Prediction

After total hip arthroplasty (THA), patient-specific biomechanical analysis is a useful tool for estimating hip joint forces, muscle activation patterns, and loading during movement; musculoskeletal modeling is a functional extension of patient-specific biomechanical analysis. The performance of an implant is not only dependent on the static alignment but also on the dynamic forces that are created during walking, walking up/down stairs, sit-to-stand motion, and other normal daily activities. Re-establishing femoral offset is a key part of this process as it impacts the abductor lever arm, soft-tissue tension, hip stability, and magnitude of joint reaction forces. Failure to restore the offset properly can cause a decrease in the abductor efficiency and gait disturbances, while too much offset can cause higher soft-tissue strain and mechanical load on the implant-bone interface [31].

Patients who are undergoing THA will typically have compensatory movement patterns that occur in their bodies before the surgery due to pain, stiffness, weakness, and changes in body loading. Biomechanical changes that can occur in unilateral hip OA include asymmetric gait, altered hip moments, compensatory trunk motion, decreased walking speed, decreased knee loading, and contralateral leg loading [32]. These adaptations can take several weeks after surgery and should be taken into account when predicting the loading of implants and rehabilitation needs after surgery.
In routine clinical practice, it is not possible to measure the forces acting inside the joints. These internal joint forces can be estimated by musculoskeletal models modeled by multibody dynamics. These models include patient-specific kinematics, ground reaction forces, muscle geometry, joint constraints, and segmental mechanics to simulate gait and quantify hip loading under patient-specific conditions [33]. In silico simulations can also be used to aid treatment planning and determine how modifications to the implant position, muscle function, rehabilitation program, and/or movement pattern would alter the postoperative mechanics [34]. By making the connection between implant alignment and functional loading and patient-specific movement behavior, musculoskeletal modeling is able to complement the finite element analysis approach. Table 2 provides a summary of different imaging, reconstruction, and computational modeling techniques employed for patient-specific THA planning.

Table 2. Imaging, Reconstruction, and Computational Modeling Approaches in Patient-Specific THA

Approach	Input Data	Main Function	Clinical Value	Reference
Modern templating	Digital radiographs and three-dimensional planning data	Estimates implant size, offset, limb length, and center of rotation	Improves preoperative planning accuracy	[19]
Computed tomography-based planning	CT images of the pelvis and femur	Enables three-dimensional reconstruction and navigation	Improves assessment of acetabular orientation and bony anatomy	[25]
Three-dimensional printing	Segmented imaging datasets	Produces anatomical models, guides, and custom implants	Supports complex reconstruction and surgical preparation	[23]
Finite element analysis	Patient-specific geometry, material properties, and loading data	Simulates stress, strain, micromotion, and fixation behavior	Predicts stress shielding and loosening risk	[27]
Musculoskeletal modeling	Gait data, joint kinematics, muscle geometry, and ground reaction forces	Estimates joint forces and muscle activation	Links implant alignment with dynamic loading	[33]

8. Spinopelvic Mobility and Functional Implant Positioning

The orientation of the functional implant is one of the most important factors in total hip arthroplasty (THA) and depends on spinopelvic mobility. Though the position of the acetabulum is usually determined by using static radiographic parameters, during standing, sitting, bending, and gait, the functional position of the acetabulum will vary as a function of pelvic tilt. The normal transition from standing to sitting position requires posterior pelvic tilt, an increase in the functional acetabular anteversion, and hip flexion accommodation. Impaired or excessive motion of the spine and pelvis may disrupt this adaptive process and predispose the prosthetic hip to impingement, edge loading, instability, or dislocation [35].
Patients who have spinal stiffness, sagittal imbalance, previous spinal fusion, degenerative lumbar disease, and the interaction between the lumbar spine, pelvis, and hip are particularly relevant. Decreased lumbar mobility may reduce pelvic compensation during postural changes, resulting in more motion occurring in the hip joint, which could lead to either the front or back of the hip impinging on the acetabulum, depending on the orientation of the hip components and activity position. Both hip and spine surgeons should be aware of these findings, as aligning the spine may affect mechanical behavior in hip surgery, and vice versa [36].
More recently, hip-spine classification systems, lateral radiographs of the hip and pelvis in the standing posture, and pelvic incidence, sacral slope, lumbar lordosis, and functional pelvic tilt are incorporated into practical THA planning. These parameters can help to identify patients who might need modified cup targets, instead of standard cup targets [37]. Instability in primary THA is especially relevant in that components can look reasonable on routine imaging, but become unstable [38]. These dynamic variables can be incorporated into patient-specific biomechanical modelling to aid in the optimal positioning of the implant with respect to its function and to minimize instability risk.

9. Wear, Impingement, and Edge Loading Prediction

Mechanical mechanisms of implant malposition and poor implant biomechanics that can adversely affect the long-term survival of total hip arthroplasty (THA) are significant, including wear, impingement, and edge loading. Despite all the advances in modern hip replacement, the relationship between the orientation of the implant in the pelvis, patient motion, joint loading, and material performance remains a key factor in influencing implant durability. Malalignment can limit the range of motion without impingement, lead to higher contact pressures, and cause more mechanical damage at the implant-bone interface or bearing surface [39].
The characteristics of bearings, lubrication, surface roughness, size of the heads, inclination of the cups, activity, and direction of loading significantly affect wear behavior. Each type of bearing (polyethylene, ceramic, and metal) has

different performance characteristics, and excessive loading of the bearing can cause wear particles to generate, which can cause osteolysis, inflammatory reaction, loosening, and revision risk. The selection of materials is not only dependent upon the positioning of the implant, but also on the contact mechanics involved, as even the most highly developed materials can fail in abnormal contact mechanics [40].

The high-level wear testing indicates that under certain mechanical conditions (such as microseparation, edge loading, third-body abrasion, high inclination, and abnormal gait loading) hip replacements could show significantly higher wear. These conditions may not be adequately represented by traditional wear simulations, and therefore, patient-specific modeling can be useful to determine high-risk mechanical conditions before surgery. [41] Advances in the development of wear-resistant materials, such as extremely cross-linked polyethylene, ceramics, coatings, and surface modification, have led to increased durability of the THA, but these developments can only partially offset suboptimal alignment or recurrent impingement [42]. Patient-specific biomechanical models can thus guide strategies for implant orientation to decrease wear, ensure stability, and increase longevity. Table 3 lists the main mechanical failure mechanism pathways and patient-specific measures for preventing failure in THA.

Table 3. Mechanical Failure Pathways and Preventive Strategies in THA

Failure Pathway	Contributing Factors	Biomechanical Consequence	Patient-Specific Prevention Strategy	Reference
Stress shielding	Stiffness mismatch between implant and bone	Proximal bone resorption and late loosening risk	Finite element-based implant and material optimization	[27]
Abnormal joint loading	Altered gait, pain adaptation, and asymmetric mechanics	Increased implant-bone interface stress	Musculoskeletal simulation and rehabilitation planning	[32]
Spinopelvic stiffness	Lumbar disease, spinal fusion, and sagittal imbalance	Reduced pelvic compensation and increased instability risk	Functional cup positioning using standing-sitting analysis	[36]
Edge loading	Cup malposition, microseparation, and abnormal contact mechanics	Increased wear and bearing surface damage	Wear prediction and orientation optimization	[41]
Material wear	Bearing material, surface roughness, head size, and loading direction	Wear debris, osteolysis, and revision risk	Material selection combined with alignment optimization	[40]

10. Integration With Robotic-Assisted and Navigation-Guided THA

Robotic and navigation-assisted total hip arthroplasty (THA) are two important platforms for patient-specific biomechanical planning to be delivered in the operating room. The goal of these technologies is to enhance the precision and consistency of acetabular cup placement, femoral preparation, restoring limb length, creating a proper offset, and positioning the components [43]. Robotic systems can combine pre-planning and imaging data with precise bone preparation and feedback in real time, enabling surgeons to perform consistent implant alignment techniques that they may not be able to achieve using manual methods. While enhancing component placement accuracy and minimizing technical outliers, early THA robotics designs focused more on the precision of component positioning, and clinical outcomes would rely on patient selection, surgical workflow, and registration. [44]

The three-dimensional planning, intra-operative verification, and position adjustment of implants according to the patient anatomy and functional goals are currently possible with robotic THA systems. These systems could be especially helpful in complicated anatomy, dysplasia, abnormal femoral version, modified pelvic morphology, or where the hip biomechanics must be restored accurately. These benefits come with some drawbacks, such as the cost, operative time, learning curve, availability of equipment, registration error, and doubts about the long-term success compared with an effective, traditional THA [45].

Experimental evidence shows that robot-assisted, computer-navigated, augmented reality-guided, patient-specific instrumentation and accelerometer-navigated techniques may yield better accuracy of implant positioning and fewer alignment outliers compared to manual techniques, but there are significant variations between studies [15]. This future could be further broadened by the use of artificial intelligence and emerging technologies that can aid in automated planning, predictive analytics, digital twins, intraoperative decision support, and risk stratification, among other applications [43]. These tools could be integrated with biomechanical modeling, which will enhance precision-based THA and extend the implant lifespan.

11. Clinical Validation, Challenges, and Future Directions

In order to be able to routinely use total hip arthroplasty (THA) to create patient-specific biomechanical models, clinical validation is still necessary. While the technical ability of these methods to achieve personalized arthroplasty has been increased by computational planning, robotic execution, artificial intelligence, and advanced imaging, the clinical benefit is yet to be proven via measurable gains in implant survivorship, functional recovery, reduction in implant-related complications, cost-effectiveness, and patient-reported outcomes [46]. AI has already impacted arthroplasty, including analyzing images, preplanning implants, predicting risk, optimizing workflows, and forecasting outcomes, but

for this to become the norm, algorithms need to be made transparent, datasets of high quality, it must be externally validated, and it should be used alongside, rather than instead of, surgeon decision-making [47].
Digital twin systems have the potential for being a very promising future direction as they can generate a virtual patient, a virtual implant, a virtual musculoskeletal load, a virtual rehabilitation pathway, and a virtual postoperative risk for every patient. With THA, these systems can enable the ongoing optimization of pre-operative plans based on imaging, gait information, wearable sensors, and longitudinal clinical outcomes. However, realizing this implementation is dependent on the availability of standardized, interoperable, regulatory-controlled, computationally reliable, and validated data in a variety of patient populations [48].
The potential of material innovation to further assist personalized reconstruction must also be considered, and involves the integration of biomechanical modelling with patient-specific scaffolds, porous materials and regenerative implant strategies. Scaffolds constructed from magnesium alloys are one example of the adaptive biomaterials that can be used to design future implants to better conform to anatomy, mechanical demands and the needs for bone repair [49]. AI tools for knee arthroplasty also indicate the potential for enhancing planning, prediction and post-operative monitoring in other types of joint replacement. Going forward, the impact of THA modeling should be given more consideration for its prospective validation, usability, ethical data governance, and its ability to provide long-term benefits. The next step is to examine approaches to personalized THA and future directions that can be achieved through the use of technology in precision arthroplasty (Table 4).

Table 4. Technology-Enabled Personalized THA and Future Directions

Technology/Direction	Role in THA	Potential Benefit	Current Limitation	Reference
Robotic-assisted THA	Executes preoperative plans using controlled bone preparation and feedback	Improves component placement consistency	Cost, learning curve, and workflow demands	[44]
Navigation-guided THA	Provides intraoperative orientation feedback	Reduces alignment outliers and improves reproducibility	Registration error and equipment dependence	[46]
Artificial intelligence	Supports planning, prediction, image analysis, and risk stratification	Enables data-driven personalized arthroplasty	Requires transparent validation and high-quality datasets	[47]
Digital twins	Creates dynamic patient-specific virtual models	May integrate imaging, gait, sensors, and outcomes for continuous prediction	Limited clinical validation and interoperability challenges	[48]
Patient-adapted biomaterials	Enables scaffolds and implants tailored to anatomy and bone regeneration	May improve biological integration and defect reconstruction	Requires long-term safety and performance evidence	[49]

Limitations and Future Directions

Technical complexity, lack of consistent model validation, large computational requirements, and imaging quality, segmentation, and biomechanical assumptions deficiencies limit patient-specific biomechanical modeling in THA. Much of the loading in many models is simplified and may not accurately reflect dynamic behaviors like walking on an irregular surface, climbing stairs, sitting, or getting up. Cost, lack of access to high-quality imaging and robotic platforms, workflow disruption, and the lack of a standardized workflow for incorporating model outputs into the surgical decision-making are also barriers to clinical translation. The long-term evidence of biomechanical modeling to decrease revision rates, increase function, and enhance implant survivability is limited.
Prospective clinical validation, multicenter datasets, standardization of modelling protocols, and direct comparison with conventional modelling are preferable for future studies. Integration of the AI, digital twins, wearable sensor data, robotic execution, and patient-reported outcomes may enhance prediction accuracy and clinical use. Future systems should be transparent, reproducible, inexpensive, and flexible for a variety of anatomical and functional patient profiles.

12. CONCLUSION

Patient-specific biomechanical modeling is a clinically relevant approach that can guide and enhance implant positioning and longevity in THA from a standardized positioning target to individual functional reconstruction. THA's success is dependent upon a combination of factors, such as implant orientation, bone quality, femoral offset, spinopelvic mobility, joint loading, material behavior, soft tissue balance, and patient activity patterns. These traditional alignment techniques still have a place but may not completely consider the anatomical and biomechanical variability, which may affect instability, impingement, edge loading, wear, stress shielding, and aseptic loosening. Imaging-based reconstruction, finite element analysis, musculoskeletal modeling, robotic assistance, navigation, artificial intelligence, and digital twin concepts can help to understand patient-specific mechanics and assist with more accurate preoperative and/or intraoperative decision making. What these tools can predict and do well is mechanical risk before implantation, and position components as per the anatomy and functional needs of the individual patient. Adoption of the technique will need to be standardized, validated in a prospective study, cost-effectiveness demonstrated, and integrated into a standardized surgical routine. Biomechanical planning for a personalized approach could play a key role in precision arthroplasty.

REFERENCES

1. Garofalo S, Morano C, Bruno L, Pagnotta L. A Comprehensive Literature Review for Total Hip Arthroplasty (THA): Part 2—Material Selection Criteria and Methods. Journal of functional biomaterials. 2025 May 18;16(5):184.
2. Teja T, Shrivastava S, Choudhary A, Rathod V, Balusani P. Optimizing acetabular positioning: a comprehensive review of contemporary strategies in total hip arthroplasty. Cureus. 2024 Apr 26;16(4).
3. Haglin JM, Eltorai AE, Gil JA, Marcaccio SE, Botero-Hincapie J, Daniels AH. Patient-Specific Orthopaedic Implants. Orthopaedic surgery. 2016 Nov;8(4):417-24.
4. Giraldo Gallego S, Rodríguez Cheu LE. 3D-printed hip prostheses with regenerative integration: a state-of-the-art comprehensive review. Frontiers in Bioengineering and Biotechnology. 2025;13:1719810.
5. Regis D, Cason M, Magnan B. Dislocation of primary total hip arthroplasty: analysis of risk factors and preventive options. World Journal of Orthopedics. 2024 Jun 18;15(6):501.
6. Rivière C, Lazic S, Villet L, Wiart Y, Allwood SM, Cobb J. Kinematic alignment technique for total hip and knee arthroplasty: the personalized implant positioning surgery. EFORT Open Reviews. 2018 Mar 29;3(3):98-105.
7. Fontalis A, Buchalter D, Mancino F, Shen T, Sculco PK, Mayman D, Haddad FS, Vigdorchik J. Contemporary insights into spinopelvic mechanics: challenges and innovations in total hip arthroplasty. The Bone & Joint Journal. 2024 Nov 1;106(11):1206-15.
8. Teja T, Shrivastava S, Choudhary A, Rathod V, Balusani P. Optimizing acetabular positioning: a comprehensive review of contemporary strategies in total hip arthroplasty. Cureus. 2024 Apr 26;16(4).
9. Vendittoli PA, Riviere C, Hirschmann MT, Bini S. Why personalized surgery is the future of hip and knee arthroplasty: a statement from the Personalized Arthroplasty Society. EFORT open reviews. 2023 Dec 1;8(12):874-82.
10. Driesman AS, Jennings JM, Yang CC, Dennis DA. Offset considerations in total hip arthroplasty. JAAOS-Journal of the American Academy of Orthopaedic Surgeons. 2024 Oct 15;32(20):921-8.
11. Galmiche R, Migaud H, Beaulé PE. Hip anatomy and biomechanics relevant to hip replacement. Personalized Hip and Knee Joint Replacement. 2020 Jul 1:9-21.
12. Dunleavy ML, Minutillo GT, Shaw JH, Paprosky WG. Prevention and Management of Instability After Total Hip Arthroplasty. Journal of the American Academy of Orthopaedic Surgeons. 2025 Nov 1;33(21):1184-92.
13. Rivière C, Lazic S, Villet L, Wiart Y, Allwood SM, Cobb J. Kinematic alignment technique for total hip and knee arthroplasty: the personalized implant positioning surgery. EFORT Open Reviews. 2018 Mar 29;3(3):98-105.
14. Miura T, Yamamoto N, Shiroshita A, Tsuge T, Saitsu A, Yoshitani J, Nakao S, Takami K. Comparison of implant placement accuracy between manual, robot-assisted, computer-navigated, augmented reality navigated, patient-specific instrumentation, and accelerometer navigated total hip arthroplasty: a systematic review and network meta-analysis. JBJS reviews. 2024 Nov 1;12(11):e24.
15. Meermans G, Grammatopoulos G, Innmann M, Beverland D. Cup placement in primary total hip arthroplasty: how to get it right without navigation or robotics. EFORT open Reviews. 2022 Jun 1;7(6):365-74.
16. Teja T, Shrivastava S, Choudhary A, Rathod V, Balusani P. Optimizing acetabular positioning: a comprehensive review of contemporary strategies in total hip arthroplasty. Cureus. 2024 Apr 26;16(4).
17. Kurmis AP. Advanced, Imageless Navigation in Contemporary THA: Optimising Acetabular Component Placement. IntechOpen; 2022 Jul 5.
18. Vigdorchik JM, Sharma AK, Jerabek SA, Mayman DJ, Sculco PK. Templating for total hip arthroplasty in the modern age. JAAOS-Journal of the American Academy of Orthopaedic Surgeons. 2021 Mar 1;29(5):e208-16.
19. Perazzini P, Trevisan M, Sembenini P, Alberton F, Laterza M, Magnan B, Marangon A. The Mako™ robotic arm-assisted total hip arthroplasty using direct anterior approach: Surgical technique, skills, and pitfalls. Acta Bio Medica: Atenei Parmensis. 2020 May 30;91(4-S):21.
20. Zagra L, Benazzo F, Dallari D, Falez F, Solarino G, D'Apolito R, Castelli CC. Current concepts in hip–spine relationships: making them practical for total hip arthroplasty. EFORT Open Reviews. 2022 Jan 11;7(1):59-69.
21. Behery OA, Poultsides L, Vigdorchik JM. Modern imaging in planning a personalized hip replacement and evaluating the spino-pelvic relationship in prosthetic instability. Personalized Hip and Knee Joint Replacement. 2020 Jul 1:143-56.
22. Woo SH, Sung MJ, Park KS, Yoon TR. Three-dimensional-printing technology in hip and pelvic surgery: current landscape. Hip & pelvis. 2020 Feb 26;32(1):1.
23. Qu Z, Yue J, Song N, Li S. Innovations in three-dimensional-printed individualized bone prosthesis materials: revolutionizing orthopedic surgery: a review. International Journal of Surgery. 2024 Oct 1;110(10):6748-62.

24. Mancino F, Fontalis A, Magan A, Plastow R, Haddad FS. The value of computed tomography scan in three-dimensional planning and intraoperative navigation in primary total hip arthroplasty. Hip & pelvis. 2024 Mar 1;36(1):26.
25. Teja T, Shrivastava S, Choudhary A, Rathod V, Balusani P. Optimizing acetabular positioning: a comprehensive review of contemporary strategies in total hip arthroplasty. Cureus. 2024 Apr 26;16(4).
26. Savio D, Bagno A. When the total hip replacement fails: A review on the stress-shielding effect. Processes. 2022 Mar 21;10(3):612.
27. Soliman MM, Chowdhury ME, Islam MT, Musharavati F, Nabil M, Hafizh M, Khandakar A, Mahmud S, Nezhad EZ, Shuzan MN, Abir FF. A review of biomaterials and associated performance metrics analysis in pre-clinical finite element model and in implementation stages for total hip implant system. Polymers. 2022 Oct 13;14(20):4308.
28. Colic K, Sedmak A. The current approach to research and design of the artificial hip prosthesis: a review. Rheumatol Orthop Med. 2016 Dec 27;1(1):1-7.
29. Ghosh R, Chanda S, Chakraborty D. Application of finite element analysis to tissue differentiation and bone remodelling approaches and their use in design optimization of orthopaedic implants: A review. International Journal for Numerical Methods in Biomedical Engineering. 2022 Oct;38(10):e3637.
30. Driesman AS, Jennings JM, Yang CC, Dennis DA. Offset considerations in total hip arthroplasty. JAAOS-Journal of the American Academy of Orthopaedic Surgeons. 2024 Oct 15;32(20):921-8.
31. Bariani JG, Pereira MA, Barro J, Silveira KA, Oliveira MR, Reis Filho LR, dos Reis VV, Machado MS, Teixeira PW, de Lima Filho EM. Biomechanical adaptations in unilateral hip and knee osteoarthritis: A systematic review of alterations during conservative management and surgical intervention.
32. Abdullah M, Hulleck AA, Katmah R, Khalaf K, El-Rich M. Multibody dynamics-based musculoskeletal modeling for gait analysis: a systematic review. Journal of neuroengineering and rehabilitation. 2024 Oct 5;21(1):178.
33. Killen BA, Falisse A, De Groote F, Jonkers I. In silico-enhanced treatment and rehabilitation planning for patients with musculoskeletal disorders: can musculoskeletal modelling and dynamic simulations really impact current clinical practice?. Applied Sciences. 2020 Oct 16;10(20):7255.
34. Lum ZC, Coury JG, Cohen JL, Dorr LD. The current knowledge on spinopelvic mobility. The Journal of Arthroplasty. 2018 Jan 1;33(1):291-6.
35. Haffer H, Adl Amini D, Perka C, Pumberger M. The impact of spinopelvic mobility on arthroplasty: implications for hip and spine surgeons. Journal of clinical medicine. 2020 Aug 8;9(8):2569.
36. Zagra L, Benazzo F, Dallari D, Falez F, Solarino G, D'Apolito R, Castelli CC. Current concepts in hip–spine relationships: making them practical for total hip arthroplasty. EFORT Open Reviews. 2022 Jan 11;7(1):59-69.
37. Grammatopoulos G, Innmann M, Phan P, Bodner R, Meermans G. Spinopelvic challenges in primary total hip arthroplasty. EFORT Open Reviews. 2023 May 1;8(5):298-312.
38. Rivière C, Harman C, Logishetty K, Van Der Straeten C. Hip replacement: Its development and future. Personalized hip and knee joint replacement. 2020 Jul 1:23-32.
39. Merola M, Affatato S. Materials for hip prostheses: a review of wear and loading considerations. Materials. 2019 Feb 5;12(3):495.
40. Zietz C, Fabry C, Reinders J, Dammer R, Kretzer JP, Bader R, Sonntag R. Wear testing of total hip replacements under severe conditions. Expert Review of Medical Devices. 2015 Jul 4;12(4):393-410.
41. Khanna R, Ong JL, Oral E, Narayan RJ. Progress in wear resistant materials for total hip arthroplasty. Coatings. 2017 Jul 9;7(7):99.
42. Andriollo L, Picchi A, Iademarco G, Fidanza A, Perticarini L, Rossi SM, Logroscino G, Benazzo F. The role of artificial intelligence and emerging technologies in advancing total hip arthroplasty. Journal of Personalized Medicine. 2025 Jan 9;15(1):21.
43. Banerjee S, Cherian JJ, Elmallah RK, Pierce TP, Jauregui JJ, Mont MA. Robot-assisted total hip arthroplasty. Expert review of medical devices. 2016 Jan 2;13(1):47-56.
44. Kouyoumdjian P, Mansour J, Assi C, Caton J, Lustig S, Coulomb R. Current concepts in robotic total hip arthroplasty. SICOT-J. 2020 Nov 27;6:45.
45. Miura T, Yamamoto N, Shiroshita A, Tsuge T, Saitsu A, Yoshitani J, Nakao S, Takami K. Comparison of implant placement accuracy between manual, robot-assisted, computer-navigated, augmented reality navigated, patient-specific instrumentation, and accelerometer navigated total hip arthroplasty: a systematic review and network meta-analysis. JBJS reviews. 2024 Nov 1;12(11):e24.
46. Chowdhury PN, Vaish A, Puranik A, Vaishya R. Artificial intelligence in arthroplasty: Past achievements, present applications, and future directions. Indian Journal of Hip and Knee Arthroplasty. 2025 May 1;1(2):77-85.
47. Diniz P, Grimm B, Garcia F, Fayad J, Ley C, Mouton C, Oeding JF, Hirschmann MT, Samuelsson K, Seil R. Digital twin systems for musculoskeletal applications: A current concepts review. Knee Surgery, Sports Traumatology, Arthroscopy. 2025 May;33(5):1892-910.
48. Manescu V, Antoniac I, Antoniac A, Laptoiu D, Paltanea G, Ciocoiu R, Nemoianu IV, Gruionu LG, Dura H. Bone regeneration induced by patient-adapted Mg alloy-based scaffolds for bone defects: present and future perspectives. Biomimetics. 2023 Dec 17;8(8):618.
49. Kim KB, Kim GB, Kim JH, Lee SM. Artificial intelligence in total knee arthroplasty: clinical applications and implications. Knee Surgery & Related Research. 2025 Oct 14;37(1):44.