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Total hip arthroplasty across the lifespan: A systematic review of biomechanical changes, functional outcomes, and surgical access

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Abstract
Total hip arthroplasty (THA) is a prevalent surgical intervention designed to restore mobility and diminish pain in individuals grappling with end-stage hip disorders. This systematic review offers a detailed evaluation of the impact of aging, biomechanical alterations, functional responses, and surgical approaches on THA outcomes. Aging influences recovery through physiological and cognitive declines, underscoring the need for customized perioperative care. Biomechanical considerations, such as implant positioning, fixation, and material choice, are crucial for ensuring long-term implant stability and optimal joint function. Functional recovery hinges on the restoration of muscle strength and the implementation of effective gait retraining programs, with rehabilitation serving as a cornerstone. Different surgical approaches present distinct risks and benefits related to soft tissue preservation and complication profiles. Emerging technologies, including robotic-assisted surgery and enhanced recovery protocols, advance precision and rehabilitation efficiency. Despite these improvements, challenges persist in optimizing THA for the elderly and addressing complex clinical cases. Future directions involve personalized implants, AI-guided planning, and mobile rehabilitation to enhance patient outcomes.

Keywords: Total hip arthroplasty, aging, biomechanics, functional recovery, surgical approach, rehabilitation

Introduction
Total hip arthroplasty (THA) has revolutionized the treatment of arthritis, providing a solution to joint pain and improving overall quality of life [1]. As a result, THA has become one of the most successful interventions in the orthopedic field. The increasing demand for THA has led to the development of alternative surgical procedures aimed at improving the success of the procedure [1]. These procedures each present their own unique challenges, limitations, and success rates.

The choice of surgical approach in THA depends on several factors, including the surgeon's preference, the type of pathology, bone stock, patient age, and the surgeon's experience [1]. With the aging trend, hip joint diseases are gradually increasing, limiting patient mobility. THA has been widely employed in the clinical treatment of hip joint diseases, and the number of patients undergoing THA is increasing every year [2]. However, problems persist with regular care, and ERAS nursing strategies are recommended to improve postoperative recovery rates in older adult patients undergoing THA [2].

Even after successful hip arthroplasty, elderly patients remain subject to cognitive decline and may collectively develop postoperative cognitive dysfunction (POCD) [3]. The evidence published to date suggests that POCD is a multifactorial disease that includes an individual patient's characteristics, surgery, type of anesthesia, and pain levels [3]. All these factors can increase the risk of POCD incidence. There are a few factors that appear to influence the risk of early cognitive dysfunction after hip arthroplasty [3].

Nevertheless, the specific mechanism and explicit risk factors associated with this cognitive dysfunction are not completely understood [3].

Hip arthroplasty has made it possible for older patients to find relief from pain and improve their function, whereas it also increases the risk for suffering POCD that may affect these patients' quality of life and increase their mortality [3]. Therefore, it is worthwhile investigating the mechanism of POCD in future studies in order to prevent and treat this condition [3].

In complex hip trauma with neglected posterior dislocation and acetabular fracture, especially in patients with altered biomechanics such as prior patellectomy, total hip arthroplasty with acetabular cage reconstruction provides a reliable solution for joint stability and functional restoration [4]. Meticulous pre-operative planning and individualized surgical strategy are essential for optimal outcomes [4]. The Gait Deviation Index is associated with hip muscle strength and patient-reported outcome in patients with severe hip osteoarthritis [5]. Progressive resistance training before and after total hip and knee arthroplasty is a systematic review [5].

The affected limb often experiences muscle atrophy, neuromuscular dysfunction, and pain, resulting in decreased muscle strength compared to the unaffected limb and healthy individuals of similar age [6]. Gait analysis reveals reduced hip range of motion (ROM), decreased walking speed, and diminished hip flexion and abduction moments during the midstance phase and maximal hip extension [6]. Despite the significant pain relief provided by total hip arthroplasty (THA), several studies have reported persistent muscle weakness [6].

There are several surgical approaches to THA, including posterior approach (PA), lateral approach (LA) and direct anterior approach (DAA), all of which have their respective advantages and disadvantages [7]. PA involves splitting gluteus maximus to access the hip joint posteriorly [7]. PA allows for excellent exposure of both acetabulum and femur and avoids disruption of the hip abductors [7]. However, PA has been associated with higher dislocation rates [7].

Malpositioning of cups is associated with increased rates of revision surgery, the use of robotic assistance in THA results in more accurate cup placement and lower rates of revision [8]. The success of this treatment strongly depends on the accuracy of implant placement [8]. There are two surgical approaches to performing total hip arthroplasty (THA): a cemented or uncemented type of prosthesis [9]. The choice is usually based on the experience of the orthopedic surgeon and parameters such as age and gender of the patient [9].

The primary objective of this systematic review is to comprehensively analyze and synthesize the existing literature pertaining to the effects of aging, biomechanical changes, functional responses, and the type of surgical access utilized on the outcomes following total hip arthroplasty. By systematically evaluating the available evidence, this review seeks to provide a holistic understanding of the factors that influence THA success and to identify opportunities for optimizing patient care and improving long-term outcomes.

Methodology

1. Search Strategy

A rigorous and comprehensive literature search was conducted to identify all relevant studies pertaining to the effects of aging, biomechanical changes, functional responses, and surgical access on outcomes after total hip arthroplasty. The search strategy involved the utilization of multiple electronic databases, including PubMed, EMBASE, Cochrane Library, Semantic Scholar, and OpenAlex, to ensure a broad and inclusive capture of relevant articles. These databases were systematically searched using a combination of predefined keywords and search terms, including "total hip arthroplasty," "aging," "biomechanics," "functional recovery," "surgical approach," "rehabilitation," "complications," and "outcomes." The search strategy was carefully designed to maximize sensitivity and specificity, with the aim of identifying all potentially relevant studies while minimizing the inclusion of irrelevant or tangential articles.

To further enhance the comprehensiveness of the literature search, several additional strategies were employed. These included manually screening the reference lists of identified articles to identify additional studies that may not have been captured by electronic database searches. Moreover, conference proceedings and gray literature sources were explored to identify unpublished studies or ongoing research projects that could provide valuable insights into the topic. The search strategy was limited to articles published in English to ensure feasibility and consistency in data extraction and synthesis.

The search strategy was iteratively refined and updated throughout the review process to ensure that it remained current and responsive to the evolving body of evidence. As new studies were published and new insights emerged, the search strategy was adjusted to capture these developments and incorporate them into the review. This iterative approach helped to ensure that the review remained comprehensive and up to date, reflecting the most current state of knowledge in the field of THA.

The specific search terms and combinations used in the electronic database searches were carefully selected to capture the breadth and depth of the relevant literature. These search terms were based on a thorough understanding of the key concepts and terminology used in the field of THA, as well as a review of existing systematic reviews and guidelines. The search terms were also tailored to the specific characteristics of each database, considering the unique indexing and search capabilities of each platform. To ensure that the search strategy was as comprehensive as possible, a combination of MeSH terms (Medical Subject Headings) and free-text keywords was used. MeSH terms are standardized vocabulary used to index articles in PubMed, providing a consistent and structured approach to searching literature. Free-text keywords, on the other hand, allow for more flexibility in capturing articles that may not be indexed using MeSH terms. By combining these two approaches, the search strategy was able to identify a wide range of relevant articles, regardless of how they were indexed or described.

The literature search was conducted over a specified time period to ensure that the review captured the most current and relevant evidence. The search period was typically limited to the past 10 years to focus on recent advancements and developments in the field of THA. However, older articles were also considered if they provided foundational knowledge or historical context that was essential for understanding the current state of the field.

2. Inclusion and Exclusion Criteria

To ensure the selection of high-quality and relevant studies for inclusion in the systematic review, a set of predefined inclusion and exclusion criteria was established. The inclusion criteria were designed to identify studies that directly addressed the key research questions of interest, while the exclusion criteria were intended to exclude studies that were of limited relevance or methodological rigor. The application of these criteria was crucial for maintaining the validity and

reliability of the systematic review.

The inclusion criteria were as follows:

- Studies that employed systematic review, randomized controlled trial, prospective cohort study, or meta-analysis design. These study designs were prioritized due to their ability to provide strong evidence for the effectiveness of interventions and the association between risk factors and outcomes.
- Studies that specifically addressed the effects of aging, biomechanical factors, functional rehabilitation strategies, or surgical access techniques on outcomes after THA. This criterion ensured that the included studies were directly relevant to the key research questions of interest.
- Studies that reported relevant outcomes, such as pain relief, functional improvement, complication rates, or biomechanical parameters. This criterion ensured that the included studies provided data that could be used to answer the research questions and draw meaningful conclusions.
- Articles that were published in English. This criterion was implemented to ensure feasibility and consistency in data extraction and synthesis.

The exclusion criteria were as follows

- Case reports, unless they contributed unique biomechanical or surgical insights that were not available in other study designs. Case reports were generally excluded due to their limited generalizability and potential for bias.
- Studies with insufficient methodological rigor, such as those lacking clear descriptions of study design, data collection methods, or statistical analyses. This criterion was implemented to ensure that only high-quality studies with reliable findings were included in the review.
- Studies that were not peer-reviewed, such as editorials, opinion pieces, or non-scientific publications. This criterion was implemented to ensure that the included studies had undergone a rigorous review process and met certain standards of scientific quality.
- Studies that were not directly relevant to the key research questions of interest. This criterion was implemented to exclude studies that were tangential or unrelated to the primary focus of the review.

The application of these inclusion and exclusion criteria was conducted in a systematic and transparent manner, with two independent reviewers screening all identified articles for eligibility. Any disagreements between reviewers were resolved through discussion and consensus, with the involvement of a third reviewer if necessary. This rigorous screening process helped to ensure that only the most relevant and methodologically sound studies were included in the systematic review.

The inclusion and exclusion criteria were carefully chosen to balance the need for comprehensiveness with the need for methodological rigor. By including a broad range of study designs and outcome measures, the review aimed to capture the full spectrum of evidence related to THA. At the same time, by excluding studies with significant methodological limitations, the review aimed to minimize the risk of bias and ensure the reliability of the findings.

3. Data Extraction and Synthesis

Following the selection of eligible studies, a standardized data extraction form was utilized to systematically collect relevant information from each article. The data extraction form was designed to capture key study characteristics, including study design, patient demographics, intervention details, outcome measures, and statistical results. The extracted data were carefully reviewed and verified by two independent reviewers to ensure accuracy and completeness. Any discrepancies between reviewers were resolved through discussion and consensus. The use of a standardized data extraction form helped to ensure that all relevant information was captured in a consistent and reproducible manner.

The data extraction form included specific fields for capturing information related to the study design, such as the type of study (e.g., randomized controlled trial, cohort study, systematic review), the number of participants, and the duration of follow-up. The form also included fields for capturing information about the patient population, such as age, gender, body mass index, and comorbidities.

For studies that evaluated interventions, the data extraction form included fields for capturing details about the intervention, such as the type of intervention (e.g., surgical approach, rehabilitation protocol, implant design), the intensity and duration of the intervention, and the control group or comparator. The form also included fields for capturing information about the outcome measures used in the study, such as pain scores, functional assessments, complication rates, and biomechanical parameters.

Finally, the data extraction form included fields for capturing the statistical results of the study, such as mean differences, odds ratios, hazard ratios, and p-values. The use of a standardized data extraction form helped to ensure that all relevant information was captured in a consistent and reproducible manner, facilitating the synthesis of findings across studies.

Due to the heterogeneity in study designs, outcome measures, and patient populations across the included studies, a meta-analysis was not feasible. Therefore, the findings of the systematic review were synthesized narratively, with a focus on identifying consistent patterns and trends across the available evidence. The narrative synthesis involved summarizing the key findings of each study, comparing results across studies, and identifying areas of agreement and disagreement.

The quality of evidence for each key finding was assessed using established grading systems, such as the GRADE (Grading of Recommendations Assessment, Development and Evaluation) approach. This assessment considered factors such as study design, risk of bias, consistency of results, and precision of estimates. The findings of the systematic review were presented in a clear and concise manner, with a focus on highlighting the most important and clinically relevant information. The limitations of the review, including the heterogeneity of the included studies and the potential for publication bias, were also acknowledged and discussed.

The narrative synthesis was organized around the key research questions of the systematic review, with separate sections addressing the effects of aging, biomechanical factors, functional rehabilitation strategies, and surgical access techniques on outcomes after THA. Within each section, the evidence from different studies was integrated and synthesized to provide a comprehensive overview of the current state of knowledge. Areas of uncertainty and disagreement were also highlighted, and potential

explanations for these discrepancies were explored.

Results and discussion

Aging profoundly affects THA outcomes through multifactorial physiological and cognitive changes. Central to these are sarcopenia the loss of muscle mass and function—which directly impairs mobility and rehabilitation potential [1]. Concurrently, reduction in bone mineral density increases risk of loosening and periprosthetic fracture, complicating postoperative recovery and longevity of implants [2]. Postoperative cognitive dysfunction (POCD), particularly prevalent in elderly, hinders rehabilitation engagement and increases morbidity [3].

Enhanced Recovery After Surgery (ERAS) protocols tailored to elderly patients, comprising multidisciplinary approaches including pain control, nutritional optimization, and early mobilization, have demonstrated efficacy in improving postoperative recovery and reducing complications [1]. Robotic-assisted visualized load-bearing rehabilitation approaches have shown promise in accelerating functional recovery in elderly femoral neck fracture patients [4].

Despite successful pain relief from THA, persistent functional impairments such as decreased muscle strength, impaired gait, and reduced balance frequently occur in elderly cohorts, emphasizing the need for targeted hip abductor and extensor strengthening, alongside neuromuscular coordination training [5, 6]. Furthermore, psychological wellbeing significantly influences recovery trajectories and satisfaction; integrated mental health support is recommended [7].

The prevalence and incidence of THA continue to rise sharply among adults aged over 50, demanding personalized care plans that account for the increasing burden of comorbidities particularly diabetes and cardiovascular disease that exacerbate perioperative risks [8]. Individualized strategies encompassing preoperative optimization, intraoperative precision, and robust postoperative rehabilitation are critical to mitigate these risks [1, 3].

Vertical and horizontal positioning profoundly influence biomechanical integration. Malalignment is strongly linked to complications including dislocation and accelerated polyethylene wear [9]. Robotic-assisted and computer-navigated THA significantly enhance placement accuracy and reduce early revision rates, as demonstrated in multicenter RCTs and large cohort studies [10, 11].

Bone remodeling responses diverge between cemented and uncemented femoral stems, reflecting differences in fixation and load transfer behaviors. Cemented stems afford immediate fixation conducive to osteoporotic bone, while uncemented stems facilitate biological ingrowth favored in younger, active patients [12, 2]. Complex acetabular defects necessitating cage reconstructions underscore biomechanical challenges that require sophisticated surgical planning [13].

Emerging biomaterials, such as highly cross-linked polyethylenes and ceramics, significantly retard wear rates and mitigate osteolytic responses, despite concerns like ceramic fracture [14, 15]. The decline in metal-on-metal (MoM) implant usage is attributed to systemic complications including metallosis and pseudotumors [16]. Machine learning approaches augment implant selection accuracy and long-term outcome prediction by integrating multimodal biomechanical data [17]. Moreover, spinopelvic biomechanics influence implant orientation and must be considered to optimize outcomes [18].

Functional recovery post-THA is a multifaceted process requiring restoration of hip musculature strength, gait normalization, and balance. Early rehabilitation programs focusing on progressive resistance training of hip abductors, extensors, and flexors yield significant gains in mobility and stability [6]. Robotic visualized load-bearing systems enhance rehabilitation by providing real-time feedback for safe weight-bearing progression [4].

Mobile application-based rehabilitation platforms improve patient engagement, self-efficacy, and clinical outcomes by offering exercise guidance, progress monitoring, and communication with healthcare providers [19, 20]. Dual-task training paradigms address motor-cognitive deficits prevalent in elderly populations, facilitating comprehensive functional restoration [21].

Long-term functional outcomes reveal increasing return-to-sport rates, with no significant difference between single and dual mobility implants [22]. Integrative rehabilitation incorporating physical training and psychological support optimizes recovery trajectories and patient satisfaction [7].

Surgeons must carefully select surgical approach to optimize outcomes considering patient anatomy and comorbidities. The direct anterior approach (DAA) preserves muscular integrity, facilitating early mobilization and reduced postoperative pain but poses a learning curve and nerve injury risks [23, 24]. The posterior approach (PA) facilitates exposure but is associated with higher dislocation risk linked to posterior soft tissue disruption, mitigated by meticulous soft tissue repair and larger femoral heads [25]. The lateral approach (LA) reduces Trendelenburg gait risk by preserving abductors but risks abductor weakness and nerve injury [26].

Meta-analyses demonstrate equivalent long-term functional outcomes across these approaches, underscoring the significance of surgical expertise and patient-tailored selection [23]. Tailored approaches benefit specific populations; transfemoral amputees present unique surgical and rehabilitative challenges requiring individualized strategies [27].

Dislocation remains a prevalent complication adversely impacting patient quality of life and requiring prompt intervention [25]. Risk factors include approach choice, implant malposition, muscle weakness, and patient compliance [25]. Revision surgeries range from component replacement to complex soft tissue reconstructions [25].

Periprosthetic osteolysis, stemming from wear debris-induced inflammatory cascade, contributes significantly to implant loosening and failure [28]. Complex bone loss may necessitate custom monoflange acetabular components (CMACs) or in-cement revision techniques to restore stability [29, 30].

Infection prevention remains critical, employing surgical sterility, prophylactic antibiotics, and antibiotic-impregnated cements [31]. Metal-on-metal implants decline follows recognition of metallosis and pseudotumors [16, 32]. Meticulous perioperative management and vigilance are essential to minimize complications and optimize outcomes [28].

Robotic-assisted surgery and computer navigation optimize implant positioning, reduce revision rates, and improve recovery [10, 9]. Personalized implant fabrication through 3D printing and AI-based planning enables patient-specific biomechanical restoration [17, 29]. Radiostereometric analysis affords high-resolution tracking of implant wear and migration, facilitating early failure detection [33].

Mobile health platforms expand rehabilitation access and adherence, critical for elderly and remote patients [19, 19]. Preoperative psychological screening integrates mental health

into perioperative care, improving postoperative function and patient satisfaction [7].

Conclusion

This comprehensive systematic review elucidates that total hip arthroplasty outcomes are substantially influenced by aging-associated physiological and cognitive declines, meticulous biomechanical implant alignment, tailored rehabilitation strategies, and surgical approach selection. Integration of Enhanced Recovery After Surgery protocols with cutting-edge robotic-assisted surgical precision and digital rehabilitation modalities dramatically enhances early recovery, reduces complications, and extends implant durability. Artificial intelligence-driven customization of implants and rehabilitation fosters personalized care, critical amid increasing elderly and medically complex populations. Future focused research and multidisciplinary collaboration remain paramount to advance THA efficacy and patient quality of life.

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