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Uncemented Total Knee Arthroplasty: An Analysis of Biomechanical, Clinical, and Technological Aspects

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Abstract

Introduction: Total knee arthroplasty (TKA) is widely used for treating advanced osteoarthritis and other degenerative conditions, providing pain relief and improved joint function. Traditionally, cemented TKA is preferred for its reliable initial fixation, especially in elderly patients with compromised bone quality. However, with increasing life expectancy and physical demands, uncemented TKA has emerged as a promising alternative, offering benefits in bone preservation and greater implant durability. This study reviews the biomechanical, clinical, and technological aspects of uncemented TKA compared to cemented TKA.

Objective: To critically evaluate the effectiveness of uncemented TKA, identifying factors that influence long-term outcomes and comparing its benefits and limitations to cemented TKA.

Methods: A review was conducted based on articles published over the last 20 years, including clinical studies, systematic reviews, experimental trials, and observational studies. The search was carried out in the PubMed, Scopus, and Web of Science databases, using specific terms and Boolean operators. Studies were selected according to predefined inclusion and exclusion criteria, and data were extracted and analyzed to compare the outcomes between TKA techniques.

Results: Uncemented TKA showed advantages in preserving bone density and reducing reoperation rates in young and active patients due to osteointegration facilitated by materials such as trabecular titanium and hydroxyapatite coatings. However, challenges persist, particularly in patients with osteoporosis, where fixation may be less effective. On the other hand, cemented TKA offers superior initial stability in older patients.

Conclusion: Uncemented TKA provides significant benefits, especially for younger patients, but the choice between cemented and uncemented TKA should be personalized, considering factors such as age, bone quality, and physical activity level. Ongoing advances in materials and technologies may further improve uncemented TKA outcomes, but additional studies are needed to strengthen the evidence.

Keywords: Knee Arthroplasty, Osteointegration, Uncemented Prosthesis, Osteoarthritis, Implant Technology

1. Introduction

Total knee arthroplasty (TKA) is widely recognized as an effective intervention for treating advanced osteoarthritis and other degenerative conditions affecting joint function. With more than one million procedures performed annually worldwide, TKA consistently demonstrates significant results in pain reduction and restoration of knee function. Traditionally, cemented prostheses have been preferred for their ability to provide reliable initial fixation, especially in elderly patients or those with compromised bone quality. However, with increasing life expectancy and physical demands of younger and more active patients, uncemented fixation has emerged as a promising alternative, offering potential for long-term bone preservation and greater implant durability [1-5].

Uncemented fixation relies on the process of osseointegration, in which bone grows directly on the implant surface, ensuring long-lasting fixation without the need for cement. The effectiveness of this process is influenced by various factors, such as bone quality, implant design, and materials used. Implants with porous surfaces or hydroxyapatite coatings, for example, have been shown to promote osseointegration and reduce loosening rates by providing an interface that facilitates cell adhesion and bone growth [6-10].

Despite advances in materials and technologies that have significantly improved the outcomes of uncemented TKA, some challenges remain. Patients with low bone density, such as those with osteoporosis, are at higher risk of fixation failure due to difficulties achieving effective osseointegration. Additionally, the wear of porous materials like trabecular titanium may become a long-term issue, particularly in patients with high physical demands, which should be considered when selecting the implant and planning the surgery [11-15].

Comparing the outcomes of cemented and uncemented TKA is crucial to determine which patient groups may benefit more from each technique. Evidence suggests that uncemented TKA may be more effective in preserving bone density and reducing the need for revision surgery in young, active patients who have longer life expectancy and higher functional demands. On the other hand, cemented TKA continues to offer significant advantages in terms of initial stability for older patients, whose bone quality may not be ideal for biological fixation [16-20].

Therefore, the objective of this integrative review is to critically examine the available evidence on the biomechanical, clinical, and technological aspects of uncemented TKA, assessing the effectiveness of this technique compared to cemented TKA. The review will analyze factors influencing long-term outcomes, with the aim of guiding clinical practice and contributing to optimizing results for different patient profiles.

2. Methodology

This integrative review aimed to synthesize available evidence on the effectiveness of uncemented total knee arthroplasty (TKA) compared to cemented TKA, focusing on biomechanical, clinical, and technological aspects. A systematic and structured approach was employed, following a series of steps to ensure comprehensive coverage and critical analysis of the topic.

The first step was to define the research problem, which centered on exploring the efficacy and outcomes associated with uncemented TKA in comparison to cemented TKA. The goal was to assess the benefits and limitations of each technique, considering biomechanical performance, clinical results, and technological innovations in implant design. This review sought to address the central question: "What is the current evidence regarding the effectiveness and challenges of uncemented TKA versus cemented TKA?"

Specific inclusion and exclusion criteria were established to guide the selection of relevant studies. For inclusion, the review considered peer-reviewed articles that directly addressed uncemented TKA and its comparisons with cemented TKA, including clinical studies, systematic reviews, experimental trials, and observational research. Articles discussing technological advances in implant design and biomechanical considerations were also eligible. Only studies published in the last 20 years were included to capture recent advancements in the field. In contrast, studies such as conference abstracts, dissertations, theses, non-peer-reviewed articles, and research that did not directly compare the TKA techniques or lacked relevant data for critical evaluation were excluded.

The literature search was conducted across three major databases: PubMed, Scopus, and Web of Science, chosen for their extensive coverage and importance in the medical field. The search strategy utilized a combination of keywords such as "uncemented knee arthroplasty," "cemented knee arthroplasty," "biomechanics," "osteoarthritis," and "prosthesis design," with Boolean operators (AND, OR) applied to ensure a broad and thorough search. This approach aimed to retrieve articles addressing various aspects of the topic to provide a comprehensive understanding.

The screening and selection process involved an initial evaluation of the titles and abstracts of the retrieved articles to assess their relevance based on the inclusion criteria. Studies that passed this initial screening underwent a full-text review to confirm their suitability and quality. This two-stage process ensured that only the most relevant and high-quality evidence was included in the review.

Data extraction and organization involved collecting key information from the selected studies, including the type of study (e.g., clinical trial, systematic review, observational study), characteristics of the participants (such as age, diagnosis, condition severity, and bone quality), details of the interventions (cemented or uncemented TKA, materials used, technological innovations), and outcomes evaluated (e.g., biomechanical stability, bone integration, clinical complications, reoperation rates, technological aspects like biocompatible materials and implant design). The authors' conclusions were also summarized to provide insights into the main findings and recommendations for clinical practice. This structured approach allowed for a comparative analysis of TKA techniques, highlighting patterns, trends, and challenges relevant to optimizing patient outcomes.

The extracted data were organized into an analysis matrix to facilitate the comparison between studies and identify patterns and discrepancies in the results. The data synthesis was conducted by grouping the evidence into key themes: Biomechanics, clinical outcomes, and technological innovations. The discussion focused on the main benefits and limitations of uncemented TKA compared to cemented TKA, considering the implications for clinical practice.

3. Results and Discussion

The bone-implant interface is a crucial factor in uncemented total knee arthroplasty (TKA), playing a decisive role in the long-term success of the procedure. The effectiveness of this approach relies on the initial stability of the implant and its durability, both of which are significantly influenced by the surrounding bone's ability to integrate with the implant surface. Porous surfaces and bioactive treatments, such as hydroxyapatite coatings, are designed to optimize the biological response, promoting osseointegration, reducing early loosening rates, and enhancing implant longevity [13-15].

Materials like trabecular titanium, which have high porosity, have shown significant potential in uncemented TKA, mainly due to their ability to mimic the structure of cancellous bone. The three-dimensional porosity of titanium creates an environment conducive to vascularization and bone growth, improving mechanical load distribution and increasing implant fixation. This is particularly relevant for younger patients, who have a longer life expectancy and higher levels of physical activity, requiring an implant that can withstand higher loads over time. Additionally, the use of hydroxyapatite coatings improves biocompatibility and implant integration, making it an especially effective strategy for patients with low bone density, providing greater security and durability [16-18].

Bone quality is a critical determinant when choosing uncemented TKA. Patients with osteoporosis or other conditions that compromise bone density are more susceptible to fixation failure, as low-density bone may not provide the necessary support for effective osseointegration. In such cases, advanced bone bed preparation techniques, such as minimizing thermal trauma and using bone grafts, are recommended to improve the bone-implant interface and encourage bone growth. Maintaining bone density around the implant is essential for long-term stability and to reduce complications such as peri-implant fractures and implant loosening [19-21].

The precision of implant placement is another crucial aspect influencing clinical outcomes in uncemented TKA. Robotic-assisted technologies and image-guided navigation have enhanced surgical accuracy, enabling intraoperative adjustments that optimize bone-implant contact. These technologies help achieve a more precise implant positioning, reducing micromovements that could impair bone formation around the implant and compromise long-term stability [22-24].

Porous-surfaced implants are designed to distribute mechanical loads evenly, minimizing "stress-shielding"—a phenomenon in which the implant's rigidity diverts loads away from the bone, leading to bone resorption. By distributing forces more evenly, these implants help preserve bone quality and reduce the risk of peri-implant fractures, which are common in patients with low bone density or osteoporosis [25-27].

The design of the implant plays an important role in the bone-implant interface. Optimized geometries for maximizing contact in high-load areas, combined with advanced surface treatments, have shown better long-term stability outcomes. Textured surfaces and three-dimensional porosity enhance mechanical anchorage, promoting more efficient bone integration and reducing the likelihood of implant failure [28-30].

The materials used in uncemented TKA, such as titanium and cobalt-chromium alloys, are selected based on their biomechanical properties and biocompatibility. Titanium is favored for its lightness, corrosion resistance, and ability to bear loads without inducing excessive "stress-shielding." On the other hand, cobalt-chromium alloys, known for their high mechanical strength, are preferred in high-load areas. However, the rigidity of these alloys can be a disadvantage, increasing the risk of implant fractures, especially in patients with high functional demands [31-33].

Implants with textured surfaces and three-dimensional porosity have been effective in promoting bone growth and improving biomechanical stability. These implants can reduce the risk of loosening, one of the main causes of long-term failure. However, the use of porous materials may increase wear in active patients, which should be considered in preoperative planning, particularly for younger and physically demanding individuals [34-36].

Cobalt-chromium alloys are especially useful in cases where wear resistance is a major concern due to their high strength. However, this rigidity can also increase the risk of fractures, particularly when load distribution is inadequate. Thus, the selection of implant material should balance wear resistance with the ability to promote osseointegration, ensuring long-term functionality [37-39].

The modularity of uncemented TKA components allows for greater customization during surgery, which is a significant advantage. This feature enables specific adjustments for each patient's anatomy, improving stability and satisfaction with the outcomes. Modularity is especially useful in revision surgeries, where adapting the implant to the remaining bone can be challenging [40-42].

Technological advancements, such as 3D printing, have revolutionized the development of customized implants designed to fit the patient's specific anatomy. The ability to personalize the implant design before surgery allows for better load distribution and improves functional outcomes, reducing the risk of complications [43-45].

Finite element simulations are widely used in the development of orthopedic implants, allowing predictions of implant behavior under different loading conditions. These simulations help optimize the design to improve force distribution and reduce localized stresses, preserving bone structure and minimizing postoperative complications [46-48].

Compared to cemented TKA, uncemented TKA offers advantages in preserving bone structure and promoting biological fixation. Biological fixation is especially important for young and active patients, as it provides more efficient osseointegration and greater freedom of movement, resulting in a lower rate of reoperations. However, in cases of advanced osteoporosis, where bone quality may be insufficient for biological fixation, cemented TKA remains the preferred option due to the initial stability provided by the cement [46-48].

The choice between cemented and uncemented TKA should be based on a personalized evaluation of patient characteristics, such as age, bone quality, physical activity level, and rehabilitation expectations. Younger patients with good bone quality are ideal candidates for uncemented fixation, while those with more fragile bones may benefit from the additional stability provided by cemented TKA [13-15].

4. Conclusion

Uncemented TKA offers substantial advantages in bone preservation and long-term stability, making it particularly well-suited for younger, more active patients. Ongoing advancements in implant materials, surgical techniques, and technological innovations hold promise for further improving clinical outcomes. However, to fully realize these benefits, it is crucial to adopt a personalized approach, carefully selecting patients based on individual factors such as bone quality, age, and activity level. Tailoring the treatment strategy to the unique characteristics of each patient will be essential for optimizing the success of uncemented TKA and ensuring durable, high-quality results across diverse patient populations.

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