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Biomechanics and biocompatibility assessment of bone drilling for surgical application: a systematic literature review

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Abstract

This systematic literature review delves into the intricate relationship between biomechanics and biocompatibility within the context of bone drilling for surgical applications. It meticulously analyzes the forces, stresses, and strains that bone undergoes during drilling, shedding light on essential variables crucial for enhancing surgical efficacy. Moreover, it scrutinizes the mechanical attributes of drilling tools, particularly drill bits, assessing factors such as material composition, design intricacies, and heat generation, all of which profoundly influence drilling performance. The review also thoroughly investigates the implications of drilling materials on bone tissue biocompatibility, addressing concerns such as corrosion, wear debris, and potential toxicity. By synthesizing current research, it offers up-to-date insights into advancements and strategies aimed at overcoming challenges in bone drilling. Ultimately, this review serves to refine bone drilling techniques, advocating for safer and more efficient surgical practices, and ultimately aiming to improve patient outcomes through a comprehensive understanding of biomechanical and biocompatibility considerations.

Keywords:
Biomechanics, biocompatibility, surgical application, bone drilling.

1 Introduction

In the realm of surgical interventions, bone drilling stands as a fundamental and ubiquitous procedure employed in orthopedic and dental surgeries. The intricate interplay between biomechanics and biocompatibility in bone drilling is of paramount importance, influencing the success of surgical outcomes and patient recovery [1]. A comprehensive examination of the current state of knowledge regarding the biomechanics involved in bone drilling and the crucial aspect of biocompatibility, with a focus on their collective impact on surgical applications, is a crucial approach [2].

Bone, with its dynamic and adaptive nature, necessitates a nuanced understanding of the biomechanics governing the drilling process [3]. The forces exerted, stresses induced, and strains experienced during drilling play a pivotal role in determining the structural integrity of bone tissue [4], [5]. As surgical techniques continue to evolve, it becomes imperative to scrutinize the mechanical considerations associated with drilling tools, including the design, materials, and thermal effects [6], [7]. Addressing issues such as thermal necrosis, a common concern in bone drilling, requires a thorough exploration of factors influencing heat generation and dissipation during the procedure [8].

Equally significant is the exploration of biocompatibility, an essential facet that directly interfaces with the biological response of the living tissue to the drilling process [9]. Corrosion, wear debris, and potential toxic effects of drilling materials must be meticulously analyzed to ensure that surgical interventions not only achieve their intended mechanical objectives but also adhere to the principles of biocompatibility [10], [11]. This review delves into the intricate relationship between drilling materials and bone tissue, examining the biocompatibility of various materials and their implications for long-term tissue response. By synthesizing current research findings, this review aspires to shed light on the intricate synergy between biomechanics and biocompatibility in bone drilling, offering insights that not only deepen our understanding of the underlying processes but also pave the way for advancements in surgical practices, ultimately enhancing patient outcomes and minimizing complications. Furthermore, this systematic review of biomechanics and biocompatibility in bone drilling for surgery is crucial for optimizing surgical outcomes. By synthesizing current research, it informs advancements in drilling techniques, fostering safer procedures. Its insights enhance understanding of drilling's mechanical and biological impacts, ultimately improving patient care and outcomes.

2 Methodology

To craft an effective systematic literature review on the biomechanics and biocompatibility of bone drilling for surgical applications, a meticulous methodology is paramount. Begin by clearly defining the problem statement followed by research objectives and criteria for inclusion/exclusion of studies. Conducting comprehensive searches across relevant databases using specific keywords, screening, and selecting articles based on predetermined eligibility criteria, and extracting and analyzing data systematically, focusing on biomechanical principles, drilling techniques, and biocompatibility aspects. Furthermore, the step jumps into synthesizing findings, identifying gaps, and critically appraising the quality of included studies. Finally, presenting results cohesively, offering insights, recommendations, and implications for future research and surgical practices.

3 Results and Discussion

3.1 Biomechanics and Mechanical Considerations

Bone drilling in surgical procedures is a complex biomechanical process that involves the application of forces, the generation of stresses, and the induction of strains on the bone tissue [12], [13]. A thorough evaluation of the biomechanics associated with bone drilling is essential for optimizing surgical techniques, minimizing potential complications, and enhancing overall patient outcomes [14].

The forces exerted during bone drilling are a critical aspect of the biomechanical analysis. As the drill penetrates the bone, it encounters resistance from the dense and hard tissue [15]. In addition, both drill bit geometry and feed rate have a significant influence on the maximum thrust forces, with a dominant influence of drill bit geometry in terms of the shape of the flutes, sharpness of cutting edges, and value of point angle [16], [17]. The differences in thrust forces between cortical and trabecular bone are substantial for all measured conditions. The measured values can be used for drill design [18].

Understanding the magnitude and direction of these forces is crucial for determining the appropriate drilling parameters, such as drill speed, feed rate, and axial load. Excessive forces can lead to complications such as microfractures, thermal necrosis, and damage to surrounding tissues [19]. Another research found that the exposure time during bone drilling far exceeds the commonly accepted threshold for thermal injury, which may prevail at significant distances from the drilled hole. Results of the study suggest that the correlation between the thermal exposure threshold for bone injury and viability should be further explored [20], [21]. Conversely, insufficient forces may result in inadequate bone removal, compromising the success of the surgical procedure. Therefore, a meticulous evaluation of the forces applied during bone drilling is imperative to establish optimal drilling conditions [22].

Stresses induced in bone during drilling are another key biomechanical consideration. The drilling process generates both compressive and tensile stresses on the bone surface [23]. High-speed rotation of the drill induces compressive stresses at the point of contact, while the drill's axial movement creates tensile stresses in the surrounding bone tissue [24]. These stresses can influence the structural integrity of the bone and may contribute to complications such as microcracks or thermal damage. Understanding the distribution and magnitude of these stresses is crucial for selecting appropriate drill designs and materials, as well as for minimizing the risk of stress-related complications [25], [26].

In addition to forces and stresses, the induction of strains on bone during drilling is a critical biomechanical parameter. Strain refers to the deformation of the bone tissue in response to applied forces [27]. Fig. 1 shows the deformation of long bones due to physical forces applied to cells. The drilling process induces strains both at the drill-bone interface and in the surrounding bone structure. Excessive strains can lead to microdamage and compromise the biomechanical stability of the bone. Evaluating strains during drilling is essential for assessing the potential for bone deformation, microfractures, and the overall mechanical response of the bone tissue to the drilling process [28].

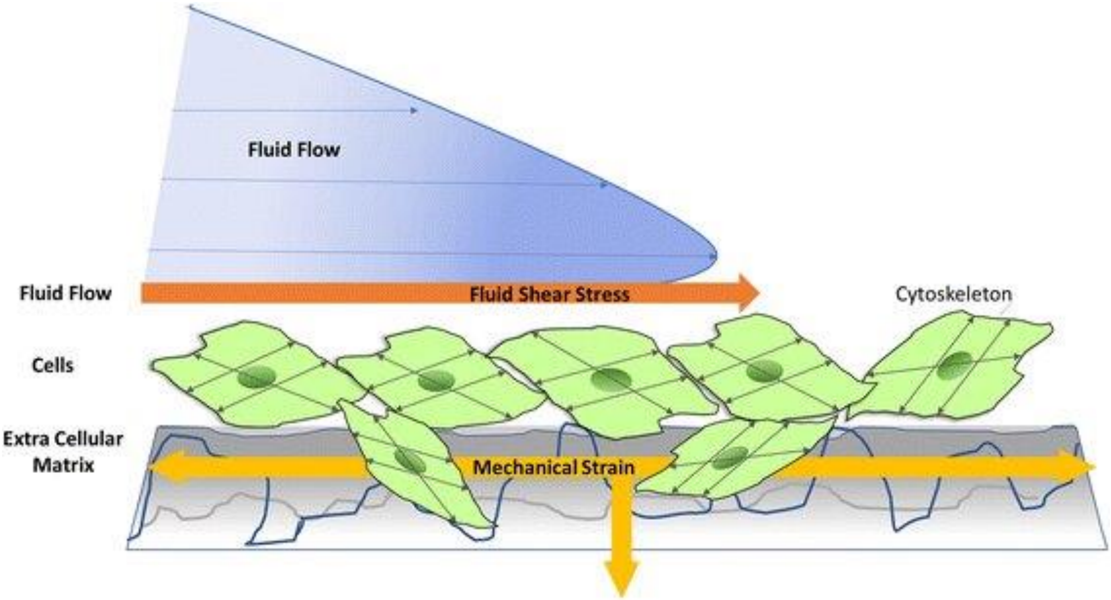

Fig. 1. The deformation of long bones results in two types of physical forces applied to cells, fluid flow-induced shear forces, and substrate deformation-induced strains, each impacting the cells of bone [28].

To comprehensively evaluate the biomechanics of bone drilling, researchers utilize various experimental and computational techniques. Experimental methods may involve the use of load cells to measure forces, strain gauges to assess strains, and high-speed imaging to capture the dynamic behavior of the drilling process [29].

Computational models, such as finite element analysis, enable researchers to simulate and analyze the distribution of forces, stresses, and strains in virtual representations of bone structures. For instance, a finite element model of the bone drilling along with the names of all its components is presented in Fig. 2 [30].

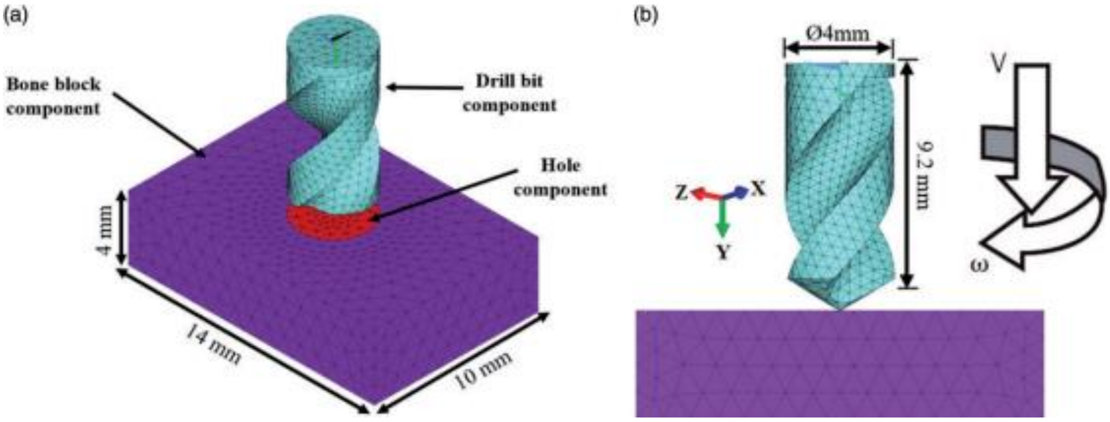

Fig 2. (a) FE model of drilling and (b) boundary conditions [30].

Advancements in imaging technologies, such as Computed Tomography (CT) and Magnetic Resonance Imaging (MRI), have also contributed to the ability to visualize and quantify the biomechanical aspects of bone drilling in vivo [31], [32]. These imaging techniques provide valuable insights into the real-time interaction between the drill and bone, allowing for a more accurate assessment of forces, stresses, and strains during the drilling process [33].

Furthermore, a thorough evaluation of the biomechanics involved in bone drilling is essential for optimizing surgical techniques and minimizing complications. The analysis of forces, stresses, and strains provides valuable insights into the mechanical interactions between the drill and bone tissue, guiding the development of safer and more effective drilling protocols [34]. As technology and research methodologies continue to advance, the understanding of bone drilling biomechanics will contribute to improved surgical outcomes and enhanced patient care in orthopedic and dental procedures [35].

The mechanical properties of drilling tools, particularly drill bits, play a pivotal role in determining the efficacy and safety of bone drilling procedures in surgical applications [36]. A comprehensive assessment of these properties involves a meticulous examination of factors such as material composition, design characteristics, and the consequential impact on bone tissue, including considerations related to heat generation. The material composition of drill bits is a critical determinant of their mechanical performance and durability [37]. Different materials exhibit distinct properties, influencing factors such as hardness, toughness, and wear resistance. Common materials used for drill bits in orthopedic and dental surgeries include stainless steel, titanium alloys, and various high-speed steels [38]. The choice of material is often dictated by the specific requirements of the surgical procedure, with considerations for factors like corrosion resistance, biocompatibility, and mechanical strength [39]. Assessing the mechanical properties of these materials is crucial for ensuring that the drill bits can withstand the demanding conditions of bone drilling without premature wear or failure [40].

Heat generation during bone drilling is a critical consideration due to its potential implications for tissue health. The mechanical interaction between the drill bit and bone tissue generates frictional heat, which, if excessive, can lead to thermal necrosis—a condition characterized by cell death due to elevated temperatures [41], [42]. The assessment of heat generation involves understanding the thermal properties of both the drill bit and the bone, as well as the dynamics of heat dissipation during the drilling process. Materials with poor thermal conductivity may contribute to increased heat accumulation, emphasizing the need for drill bit designs that facilitate efficient cooling, perhaps through integrated irrigation systems [43], [44].

3.2 Biocompatibility and Tissue Response

The biocompatibility of drilling materials is a critical aspect of bone drilling in surgical applications, directly influencing the interaction between the implanted materials and the living bone tissue. A comprehensive examination of biocompatibility involves assessing potential issues such as corrosion, wear debris, and the risk of toxic effects on bone tissue [45]. Corrosion resistance is a key consideration in the evaluation of drilling materials for bone surgery. Corrosion can compromise the structural integrity of the drilling tools and release metallic ions into the surrounding tissue, potentially leading to adverse biological reactions [46]. Recent studies have focused on the development and characterization of corrosion-resistant materials for drill bits, such as titanium alloys and advanced stainless steels. These materials exhibit improved corrosion resistance, reducing the likelihood of material degradation and mitigating the risk of detrimental effects on bone tissue [47], [48], [49].

Wear debris generated during bone drilling poses another potential challenge to biocompatibility. The mechanical abrasion of drill bits can result in the production of wear particles that may be released into the surgical site [50]. These particles have the potential to induce inflammatory responses and compromise the biocompatibility of the drilling process. Recent research has delved into the characterization of wear debris and the development of coatings or surface modifications that minimize wear, consequently reducing the release of debris and enhancing the biocompatibility of drilling materials [51], [52].

The potential toxic effects of drilling materials on bone tissue have also been a subject of investigation. Certain materials used in drilling tools may release ions or byproducts that can have cytotoxic or inflammatory effects on surrounding cells. Researchers have explored the toxicological aspects of drilling materials, considering the impact on bone cells and the overall tissue response [53], [54]. Recent studies have focused on understanding the specific mechanisms underlying potential toxicity and developing materials that pose minimal risk to the biological environment. Biocompatibility assessments also extend to the design and surface modifications of drill bits [55]. The topography and chemistry of the material surface can influence cellular response and tissue integration. Recent literature has highlighted the importance of surface engineering techniques, such as coatings and texture modifications, in enhancing the biocompatibility of drilling materials. These approaches aim to promote osseo integration, reduce inflammation, and improve the overall compatibility of the drilling tools with the surrounding bone tissues [56].

3.3 Clinical Implications

Clinical implications derived from research on the biomechanics and biocompatibility of bone drilling for surgical applications are profound and multifaceted [57]. This systematic literature review explores the implications of these findings on surgical practices, patient outcomes, and the broader field of orthopedic surgery. First and foremost, understanding the biomechanics of bone drilling is paramount for optimizing surgical outcomes. By comprehensively analyzing the forces, stresses, and strains involved during drilling, surgeons can tailor their techniques to minimize bone damage and enhance stability [58]. For instance, knowledge of optimal drilling speeds and forces can help prevent overheating and necrosis of surrounding tissues, reducing the risk of complications such as delayed healing or infection. Additionally, insights into drill bit geometry and design can facilitate the selection of appropriate tools for specific surgical procedures, ensuring precision and efficacy [59].

The biocompatibility of drilling materials plays a crucial role in patient safety and postoperative recovery. This review highlights the importance of selecting materials that minimize adverse tissue reactions and promote favorable healing responses [60]. For example, biocompatible coatings or surface modifications can reduce friction and wear during drilling, thereby decreasing the release of debris and mitigating the risk of inflammatory responses or implant loosening. Additionally, the compatibility of drilling materials with surrounding tissues influences the long-term success of surgical implants, as poor biocompatibility can lead to complications such as implant rejection or osteolysis [61].

Incorporating biomechanical and biocompatibility considerations into surgical practices can have tangible benefits for patient care. By optimizing drilling techniques and selecting materials with favorable mechanical and biological properties, surgeons can minimize intraoperative complications and improve surgical outcomes [62]. For instance, a thorough understanding of bone biomechanics may inform the placement and trajectory of orthopedic implants, reducing the risk of malpositioning or implant failure. Similarly, using biocompatible drilling materials can enhance implant integration and long-term stability, leading to improved functional outcomes and patient satisfaction [63].

Moreover, the insights gained from this review have broader implications for the field of orthopedic surgery. By elucidating the complex interplay between biomechanics and biocompatibility in bone drilling, this research advances our understanding of musculoskeletal physiology and surgical biomechanics [64].

These insights may inform the development of novel surgical techniques, instrumentation, and biomaterials, driving innovation and improvement in orthopedic care. For example, emerging technologies such as patient-specific implants or 3D-printed surgical guides capitalize on our understanding of bone biomechanics to optimize surgical precision and patient outcomes [65].

Additionally, this review underscores the importance of interdisciplinary collaboration between surgeons, engineers, and materials scientists in advancing orthopedic surgery. By leveraging expertise from multiple disciplines, researchers can develop innovative solutions to longstanding challenges in bone drilling and implantation. For instance, collaborations between biomechanical engineers and orthopedic surgeons may lead to the development of next-generation drilling tools with enhanced performance and biocompatibility.

4 Conclusion

In conclusion, this comprehensive review has delved into the intricate interplay of biomechanics and biocompatibility in bone drilling for surgical applications. Through an exploration of forces, stresses, and strains imposed on bone during drilling, along with an assessment of the mechanical properties of drill bits and their impact on bone tissue, a nuanced understanding of the complexities involved in this essential surgical procedure has been achieved. The examination of biocompatibility issues, including corrosion, wear debris, and potential toxic effects, has highlighted the importance of advancing materials and surface modifications to ensure the safety and efficacy of bone drilling. As surgical technologies continue to evolve, bridging the biomechanical and biocompatibility aspects holds the key to refining drilling protocols, minimizing complications, and ultimately improving patient outcomes in orthopedic and dental surgeries. Furthermore, in conclusion, research on the biomechanics and biocompatibility of bone drilling for surgical applications has far-reaching clinical implications. By optimizing surgical techniques, selecting biocompatible materials, and advancing our understanding of musculoskeletal physiology, this research enhances patient care and drives innovation in orthopedic surgery. Ultimately, integrating biomechanical and biocompatibility considerations into surgical practices holds the potential to improve outcomes and quality of life for patients undergoing orthopedic procedures.

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