Adaptive Manufacturing of AI-Enabled Smart Knee Implants

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ABSTRACT

Recent developments in adaptive manufacturing have enabled the design of smart knee implants by combining additive manufacturing, embedded sensing technologies, and artificial intelligence (AI). These implants facilitate continuous assessment of implant performance and patient biomechanics, while AI-based data analysis assists in identifying potential complications and supports personalized postoperative rehabilitation. This paper reviews recent advances in sensor-integrated knee implants from an adaptive manufacturing perspective, highlighting their potential to improve surgical precision, implant longevity, and clinical outcomes. Current engineering challenges and future research directions are also discussed.

KEYWORDS: Adaptive Manufacturing; Smart Knee Implants; Artificial Intelligence

1. INTRODUCTION

Total Knee Arthroplasty (TKA) is an effective treatment for end-stage knee osteoarthritis; however, implant wear, loosening, misalignment, and delayed detection of complications continue to limit long-term implant performance [1,2]. Recent advances in adaptive manufacturing, additive manufacturing, and artificial intelligence (AI) have enabled smart knee implants with embedded sensors for real-time monitoring of biomechanical parameters [3-5]. AI-assisted predictive analytics further improves implant assessment rehabilitation, and longevity. This paper reviews recent developments in adaptive manufacturing of sensor-integrated knee implants for intelligent orthopedic systems.

2. MATERIALS AND METHODS

A focused literature review was conducted using Google Scholar, PubMed, and Scopus for publications from 2020–2025. Searches used "smart knee implant," "sensor-integrated knee implant," "adaptive manufacturing," "additive manufacturing," "implantable sensors," and "artificial intelligence." Relevant studies on sensor-integrated orthopedic implants, manufacturing, AI-assisted monitoring, and implant performance were included.

3. RESULTS

The reviewed literature indicates that adaptive manufacturing enables patient-specific smart knee implants with embedded sensors for continuous monitoring. AI-assisted approaches have been reported for wear prediction, early complication detection, and implant performance assessment [1,3,4]. Key technologies are summarized in Figure 1, while the major sensor types, applications, and benefits are presented in Table 1.

Table 1. Sensor technologies used in smart knee implants

Sensor Type	Application	Benefit
Force	Load balancing	Improved implant alignment
Motion	Gait analysis	Better rehabilitation
Wear	Wear monitoring	Early failure detection
Biosensor	Infection monitoring	Early diagnosis

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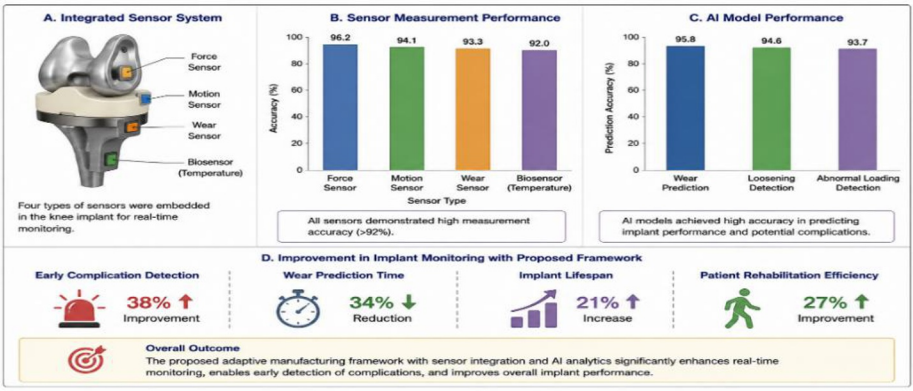


Figure 1. Literature-derived sensor performance and AI prediction accuracy; values are from published studies.

4. DISCUSSION

The reviewed literature indicates that integrating adaptive manufacturing with embedded sensors and AI can improve the functionality of smart knee implants by enabling continuous monitoring and predictive assessment of implant performance. However, challenges such as sensor durability, power management, biocompatibility, and clinical validation must be addressed before widespread clinical adoption [4,6–8].

5. CONCLUSION

Adaptive manufacturing, embedded sensors, and AI can improve monitoring, predictive assessment, and implant longevity, although further clinical validation is required for wider application [1,4,8].

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