AI-Driven Patient-Specific Knee Implant Sizing and Design Using Medical Image Analysis and Additive Manufacturing

Yogesh Ramraje Khalate [1], Tejaswini Bhosale[1,*]

[1] MIT Art Design & Technology University, Pune, India
* Correspondence: tejaswini.bhosale@mituniversity.edu.in

ABSTRACT

Total Knee Arthroplasty (TKA) is a common procedure used in patients with severely affected knee joints due to trauma, osteoarthritis and severe knee degeneration. Traditional knee implants are, however, available in fixed sizes, which are often not suitable for all patients, depending on their anatomical features. If the implant is not sized properly, it can be poorly positioned, lead to abnormal load distribution, implant loosening, discomfort and reduced functional ability after surgery. As a result, precise assessment of the dimensional characteristics of a patient's knee is crucial for selecting implants and surgical outcomes. Customized knee implants based on individual anatomical measurements can be developed due to recent developments in artificial intelligence (AI), medical image processing, three-dimensional (3D) reconstruction and additive manufacturing (AM).
KEYWORD: Knee arthroplasty; Personalise Implant; Predefined size; additive manufacturing

1. INTRODUCTION

The correct size implant is important for a knee replacement for correct anatomical fit and function. Typical implants come in standard sizes, though, which might not fit the anatomy of each individual patient. This inspires the application of AI in the accurate measurement and design of knee implants for individual patients. AM offers a promising pathway to realize these customized designs as 3D-printed implants that are more geometrically flexible and waste less material. The purpose of this study is to propose a workflow of AI-based knee measurement, personalised implant design and fabrication by 3D printing with titanium material, which will enable personalised and efficient manufacture of knee implants.

The research on AI and anatomical analysis for personalized knee implants, as presented in the Burge studies, offers significant promise for the future of medical technology and patient care [1]. Burge et al. showed automated implant customization with Computed Tomography (CT) [1] and Keskinis et al. highlighted patient-specific 3D-printed solutions during knee arthroplasty [2]. Deshmukh et al. presented a demonstration of titanium wire AM, which was used in the present work as a stepping stone for personalized measurement, implant design and fabrication using titanium [3].

2. MATERIALS AND METHODS

In the proposed framework, deep learning is combined with patient-specific implant design and fused deposition modelling (FDM) in a single workflow. Intensity normalization, noise cleaning and contrast enhancement are initial steps in pre-processing high-resolution 2D axial CT images. The YOLOv10 technology is used to segment the femur and tibia, and the morphological processing is used to refine the bone boundaries extracted in the femur and tibia [4]. Anatomical landmarks are then detected in a landmark-detection network and automatic estimation of the parameters of anteroposterior length, Medio lateral width, condylar dimensions, tibial plateau geometry and alignment parameters is possible. These measurements are applied to create a patient-specific CAD implant in parametric modelling. The geometry optimization results are then translated into an STL format, and the optimized geometry is manufactured through FDM.

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3. RESULTS

The proposed AI framework accurately extracted patient-specific knee measurements, generated customized implant geometry, and FDM successfully translated the optimized CAD design into a personalized knee implant. Figure 1 shows the result at different level.

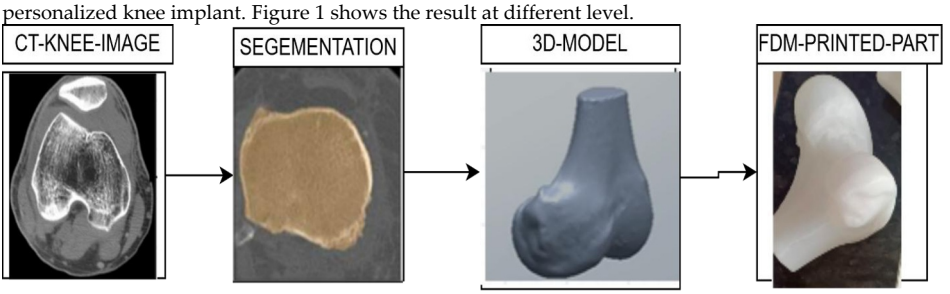


Figure 1: Multimodal architectural stepwise results for implant.

4. DISCUSSION

The proposed framework shows the feasibility of using AI-based anatomical segmentation and automated measurement to improve patient-specific knee implant sizing. By establishing an end-to-end digital pipeline, this approach streamlines the extraction of subject-specific geometric parameters from volumetric imaging data. FDM offers a systematic way to move from personalized geometry to physical fabrication.

5. CONCLUSION

The framework combines automation of anatomical measurement, patient-specific CAD design, based validation and offering an integrated approach to developing patient-specific knee implants using AI assistance. The method provides the possibility of optimizing the fit of the implant, minimizing the sizing error and manufacturing of custom-made implants. It needs more experiments and clinical data to prove its mechanical properties in the long term and its clinical feasibility.

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