Advance Sustainable Science, Engineering and Technology (ASSET)
Vol. 8, No.2, April 2026, pp. 02602014-01 ~ 02602014-013
ISSN: 2715-4211 DOI: https://doi.org/10.26877/asset.v8i2.2760

Cam Simulation and Dimensional Verification of CNC-Machined Orthopaedic Femoral Components: Toolpath Optimization and 3D-Scan Metrology

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Abstract. This study investigates the optimization of manufacturing femoral components for Total Knee Replacement (TKR) using Computer-Aided Manufacturing (CAM) simulation and 5-axis CNC milling, followed by dimensional verification based on 3D scanning. The machining process was simulated in Autodesk PowerMill to generate collision-free toolpaths for AISI 316L stainless steel. Dimensional verification was conducted by comparing the 3D-scanned physical model (using

Creality CR-Scan Ferret Pro) with the original CAD model in Geomagic Control X. The metrological analysis showed a Root Mean Square (RMS) deviation of 0.5317 mm and an average positive deviation of 0.2572 mm. Spatial deviation analysis revealed significant dimensional variations, with a maximum deviation of +2.5761 mm and a minimum deviation of -2.5713 mm. Specifically, in critical functional regions, the medial and lateral condyles exhibited deviations ranging from -0.4683 mm to 0.232 mm, while the patellar groove showed a deviation of 0.1989 mm. Although the machining strategy successfully produced the complex implant geometry, the tolerance distribution data indicated that only 17.22% of the surface fell within the strictly specified tolerances, highlighting the need for further optimization of cutting parameters and fixturing strategies to minimize surface roughness and dimensional inaccuracies.

Keywords: CAM simulation, 5-axis CNC, total knee replacement (TKR), 3D scanning, RMS deviation, dimensional metrology.

(Received 2025-09-16, Revised 2026-02-11, Accepted 2026-02-08, Available Online by 2026-03-31)

1. Introduction

One of the most common problems in human anatomy is the knee joint. It is also one of the most delicate parts of the body. Due to its complex structure and multiple joints, the knee is one of the body's most intricate components. This complexity results from the interaction of muscle and tendon mechanisms that alter the anatomical structure. In medical terms, the knee is a joint formed by the articulation of the tibia and femur. The end of the tibia is called the tibial, and the end of the femur is known as the femoral. The knee joint includes a connective tissue called articular cartilage and three bones: the femur, patella, and tibia, as shown in Figure 1A. An artificial knee replacement consists of three main parts. The femoral component (top part) replaces the lower surface of the femur and the groove where the patella fits. The tibial component (bottom part) replaces the top surface of the tibia. The patella component (kneecap part) replaces the surface of the patella that glides in the groove on the femur, as shown in Figure 1B. These elements are often anatomically shaped or contoured, rather than basic geometric shapes. They are produced in various sizes, which can be selected during surgery to match the patient's needs.to match the patient's requirements. [1]

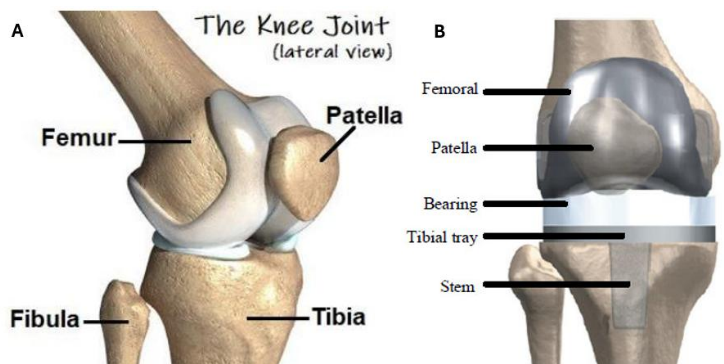


Figure 1. A) Lateral view of the knee joint [2]. B) Schematic illustration of the anatomy of the total knee prosthesis [3].

Total Knee Replacement (TKR) is a critical surgical intervention designed to restore function in patients with severe joint degradation. The success of this procedure relies heavily on the precise geometry of the implant components, particularly the femoral component, which must replicate the complex kinematics of the natural knee joint. The femoral component is characterized by intricate, sculptured surfaces that require high geometric accuracy to ensure proper alignment, minimize wear, and achieve the necessary surface flatness for long-term implant survival. [4].

While the clinical requirements for TKR are well established, manufacturing these components presents significant engineering challenges. The femoral component features freeform surfaces with varying curvatures that are difficult to machine using conventional 3-axis milling due to limited tool access and the risk of undercutting. Consequently, 5-axis Computer Numerical Control (CNC) milling has become the preferred method, as it allows for simultaneous movement along five axes, enabling the creation of complex geometries with fewer setups and minimal repositioning. [5]. However, the use of 5-axis machining introduces complexities in toolpath generation, particularly in collision avoidance and in optimizing cutting parameters to prevent surface chatter. Furthermore, the organic shape of the femoral component complicates the fixturing strategy; traditional clamping methods often obstruct toolpaths or fail to secure the irregular geometry effectively, necessitating multi-stage machining. [6].

In addition to fabrication challenges, the dimensional verification of these freeform surfaces is a critical metrological hurdle. Traditional measurement methods may struggle to capture the holistic profile of the articulating surfaces efficiently. Therefore, advanced dimensional analysis using 3D scanning technology and deviation analysis software has emerged as a vital quality assurance step to compare machined profiles directly against Computer-Aided Design (CAD) models. [7]. Previous studies have utilized CNC simulation and rapid prototyping. Yet, discrepancies between the designed and manufactured contours often persist, highlighting the need for integrated process planning that combines rigorous CAM simulation with post-process metrological validation. [8].

This study aims to bridge the gap between CAM simulation and physical realization by validating a manufacturing workflow for AISI 316L femoral components. Specifically, the objective of this research is to verify whether a two-phase 5-axis CNC machining strategy, optimized via Autodesk PowerMill simulation, can produce femoral components within a geometric tolerance of ±0.3 mm relative to the CAD model. We hypothesize that using a collision-free toolpath strategy with optimized feed rates and spindle speeds will produce a component that meets the dimensional accuracy and surface roughness requirements essential for orthopaedic applications, as verified by high-resolution 3D scanning. Design of Geometry and the Machining process of the femoral component.

2. **Methods**

The research methodology initiates with the femoral component design and CAM simulation using Autodesk PowerMill to optimize 5-axis toolpaths and generate G-code. This is followed by the physical fabrication of AISI 316L stainless steel via CNC milling, which is systematically divided into roughing, semi-finishing, and finishing stages. [9]. The process concludes with dimensional verification, where the manufactured surface is digitized using 3D scanning and analyzed in Geomagic Control X to quantify spatial deviations and RMS errors against the reference CAD model.

2.1 Design of the Knee Implant Components

Total Knee Replacement (TKR) requires precision because each shape is crucial to achieving proper alignment, optimal joint movement, and balance during installation. The flatness of the TKR component's surface must be suitable for maximum long-term use. It is reported that using Computerised Numerical Control (CNC) milling machines in the manufacturing process of TKR components can achieve high precision, with a surface flatness of 0.15-0.29 mm. [10].

[11] Introduced a new knee simulation machine to test the kinematics of TKR. The machine they studied can operate more realistically than previous models, which exhibited several weaknesses, including reduced accuracy in representing forces on various knee implant components and insufficient constraints. [12] A new design method for knee implants is proposed, based on computed tomography (CT) data, which provides a more accurate representation of the actual geometry of the knee components and reduces the possibility of implant detachment. [13] CT data is also used to design and fabricate femoral components using rapid prototyping and computer numerical control (CNC) machining methods. Finally, Song et al. (2014) presented a comprehensive study on the rapid manufacturing of femoral components using Selective Laser Melting (SLM), which offers a reliable approach to producing customised implants. The results of all the work mentioned above can produce helpful guidelines for manufacturing knee implants. Furthermore, Lu et al. (2006) Take an integrated approach to computer-aided design and manufacturing for

the femoral component of a knee prosthesis. The system is implemented based on the surgeon's requirements, from initiating the manufacturing process to completion. CAD/CAM techniques are applied to fulfil complex surface designs. With this method, surface roughness varies significantly with changes in surface curvature, and the influence of process parameters on surface quality also depends on surface curvature. [16]. General recommendations for milling operations about material implants, as can also be seen in Table 1

Table 1. General Recommendations for Milling Operations. [17]

No	Material	Cutting Tool	General-purpose starting conditions		Range of conditions	
			Feed mm/tooth	Speed m/min	Feed mm/tooth	Speed m/min
1	Low-carbon and free-machining steels	Uncoated carbide, coated carbide, cermets	0.13-0.20	120-180	0.085-0.38	90-425
2	Alloy steels Soft	Uncoated, coated cermets	0.10-0.18	90-170	0.08-0.30	60-370
	Hard	Cermets, PcBN	0.10-0.15	180-210	0.08-0.25	75-460
3	Cast iron, gray Soft	Uncoated, coated, cermets, SiN	0.10-10.20	120-760	0.08-0.38	90-1370
	Hard	Cermets, SiN, PcBN	0.10-0.20	120-210	0.08-0.38	90-460
4	Stainless steel, Austenitic	Uncoated, coated cermets	0.13-0.18	120-370	0.08-0.38	90-500
5	High-temperature alloys Nickel based	Uncoated, coated, cermets, SiN, PcBN	0.10-0.18	30-370	0.08-0.38	30-550
6	Titanium alloys	Uncoated, coated cermets	0.13-0.15	50-60	0.08-0.38	40-140
7	Aluminium alloys Free machining	Uncoated, coated, PCD	0.13-0.23	610-900	0.08-0.46	300-3000
8	High silicon	PCD	0.13	610	0.08-0.38	370-910
9	Copper alloys	Uncoated, coated, PCD	0.13-0.23	300-760	0.08-0.46	90-1070
10	Plastics	Uncoated, coated, PCD	0.13-0.23	270-460	0.08-0.46	90-1370

Source: Based on data from Kennametal Inc.

The design of the knee implant parts and the geometry of both total and partial knee implant components are defined in detail. More specifically, for the present work, it is assumed that the total knee implant, as designed, corresponds to the left knee of a male human with constrained rotational movement. The knee implant components, intended as an assembly, include the femoral, tibial, articulating surface, and patellar components, as shown in Figure 2.

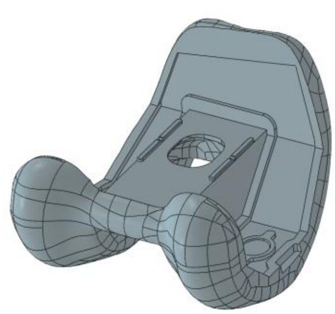


Figure 2. Parts of the designed knee replacement

2.2 *Design of the Machining Process of the Femoral Component*

After carefully designing the components of the total knee implant in accordance with international standards and relevant requirements, attention shifted to the machining of the femoral component. The machining process design for this component, which features complex geometrical shapes, necessitates specialised Computer-Aided Manufacturing (CAM) software, such as PowerMill, which can be accessed through SolidWorks. The machining of complex, sculptured surfaces is vital across industries such as automotive, aerospace, optical components, and bioengineering. One of the primary challenges in machining such surfaces is minimising machining time, as achieving the required dimensional accuracy and surface quality is considerably difficult. In addition to using cutting tools with unique geometries, the machining strategy must be meticulously planned to achieve the desired geometrical features, and appropriate process parameters must also be established. Thus, all of these tasks must be adequately addressed by utilising CAM software to machine the femoral component. CAM software is specialised to assist in various stages of product manufacturing. Most commonly, they involve an integrated Computer-Aided Design (CAD) editor or, as with Powermill, are integrated into the CAD software framework. Their purpose is to ultimately produce the code (G-Code) that controls CNC machine tools, enabling the manufacture of the desired parts. Using this type of software, details of the machining process, such as the selection of suitable cutting tools and their characteristics, the desired operations on the workpiece (e.g., hole drilling, contouring), process parameters for the various stages, and machining strategies, can be entered initially. Subsequently, G-code can be generated based on the CNC machine type, provided an appropriate post-processor is available. Furthermore, a simulation of the intended machining operations can be performed to verify that the machining will be conducted safely and aligned with the desired goals, or to identify potential errors and make necessary adjustments.

2.3 *Initial Machining Test*

After the definition of machining operations and production of G-code in the CAM software and after the simulation of the machining processes was successfully finished, it was decided that a test run, replicating the machining process in the actual CNC machining, was necessary before the final machining process to ensure that the generated G-code was producing an accurate and reliable outcome and verify the simulation results. Furthermore, it is essential to test the behaviour of the cutting tools during machining to select process parameters that prevent chattering, as this cannot be determined solely from CAM software simulations. The test run on a cylindrical polymer bulk was successful, indicating that the actual machining process can be performed without issues. After the definition of machining operations and production of G-code in the CAM software and after the simulation of the machining processes was successfully finished, it was decided that a test run, replicating the machining process in the actual CNC machining, was necessary before the final machining process to ensure that the generated G-code was producing an accurate and reliable outcome and verify the simulation results. Furthermore, it is essential to test the behaviour of cutting tools during machining to select process parameters that prevent chatter, as this cannot be determined by CAM simulation. The test run on a cylindrical polymer bulk was successful, indicating that the actual machining process can be performed without issues.

2.4 *CAM, Machining, and 3D Scanning the Femoral Component*

CAM simulation is used to generate tool motion on fabrication machines, such as 5-axis CNC milling machines. Two CAM simulations are performed on femur components for each of the 5-axis machines, which operate under different operating systems and tool-motion principles. Parameters such as cutting speed, depth of cut, and feed rate are set based on the specific conditions being studied. The CAM simulation then outputs G-code, a language recognised by CNC milling machines. CAM simulation uses Autodesk PowerMill software. After the simulation is validated and confirmed to be safe and efficient, Autodesk PowerMill performs post-processing. At this stage, the software translates the virtual machining strategy into a specific programming language that the machine can understand. The result of this post-processing is G-code, which is an NC (Numerical Control) program. G-code is a standard language containing a series of alphanumeric instructions recognized by the CNC (Computer Numerical Control) milling machine controller, which regulates axis movement, spindle speed, feed rate, and other functions. A critical step after the G-code is generated is the final verification of the NC program. This verification is essential to ensure that the code sent to the machine is 100% accurate and conforms to the expected parameters. The data from the verification of the CNC machine NC program used in this study are presented in detail in Table 2.

Table 2. Machining parameters and tool specifications used for AISI 316L femoral component fabrication.

Operation Phase	Tool Type	Diameter (mm)	Spindle Speed (n, rpm)	Feed Rate (Vf, mm/min)	Depth of Cut (mm)	Step-over (mm)	Est. Machining Time (min)
Roughing	Flat End Mill	10	2,500	800	1.0	4.0	25
Semi-Finishing	Ball Nose Mill	8	3,200	600	0.3	0.5	45
Finishing	Ball Nose Mill	6	4,500	450	0.1	0.15	90
Total Time							**160**

The machining process was divided into three stages: roughing, semi-finishing, and finishing. A Ø10 mm flat-end mill was selected for the roughing stage to maximize material removal rate (MRR) at a depth of cut of 1.0 mm. For the critical finishing stage, a Ø6 mm ball-nose end mill was used at a high spindle speed of 4,500 rpm and a fine step-over of 0.15 mm to minimize scallop height and achieve the required surface roughness for the articulation surface. The total machining time for one femoral component was approximately 160 minutes. The finishing stage accounted for the majority of this duration (approx. 56%) due to the low step-over value (0.15 mm) and conservative feed rate (450 mm/min) required to ensure the surface roughness met the strict medical requirements for articulating surfaces. This cycle time demonstrates a viable balance between production efficiency and the high geometric fidelity demanded by TKR implants.

The primary challenge in this work is that the outer and inner surfaces of the femoral component are sculptured, making it difficult to mount the workpiece on the machining centre bed. For this reason, it is considered more appropriate to perform the machining process in two separate phases. During the first phase, as shown in Figure 3, the internal surface of the femoral component is created. In the second phase, as shown in Figure 4, the workpiece is reversed, and machining of the outer surface occurs. Thus, different coordinate systems will be defined for the two stages and the stock and target materials in the CAM software.

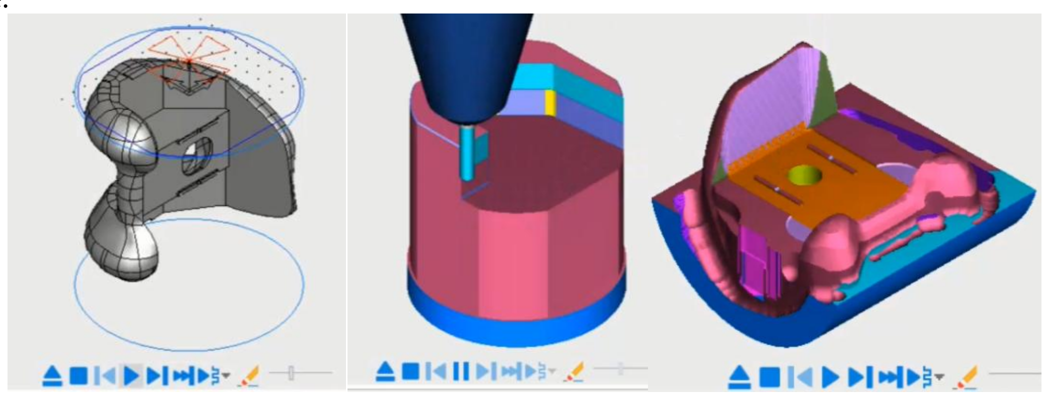


Figure 3. Snapshots from the simulation of the machining stage 1

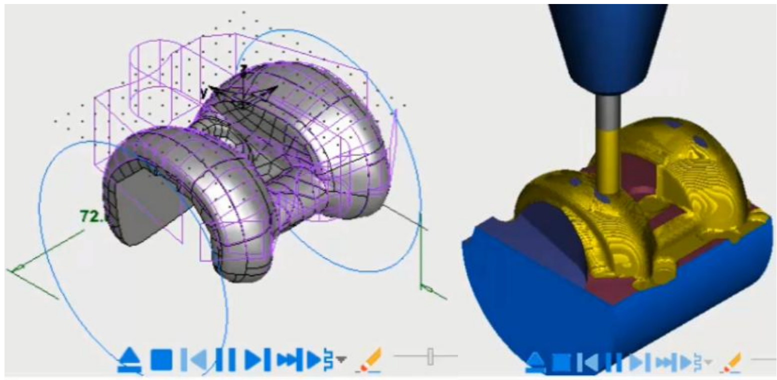


Figure 4. Snapshots from the simulation of the machining stage 2

Once the design is finalised, CAM software takes the 3D model from CAD and generates instructions for computer numerically controlled (CNC) machines. These instructions control the cutting tools to precisely machine the implant components from materials such as 316L stainless steel [18]. CAM software can also simulate the machining process itself, ensuring there are no tool collisions or gouging during manufacturing. The simulation provides a visual representation of how the material is being removed layer by layer, ensuring that the final geometry of the TKR matches the CAD design specifications. It verifies that all features (e.g., holes, contours, surfaces) are being machined correctly without overcutting or undercutting. For complex geometries like TKR, this is essential to prevent defects in the final part. CAM software predicts the surface finish of the knee joint based on cutting parameters and the selected tool [19]. This is especially important for TKR, as smooth surfaces are necessary to reduce friction in the joint. The simulation can help identify whether additional polishing or finishing steps are needed to achieve the desired surface quality. As shown in Figure 5. However, only two processes are demonstrated: the initial machining with an end mill and the finishing with a ball-nose mill, resulting in relatively good surface roughness. Kumbhalkar performed a toolpath simulation using a 5-axis CNC in 2011, whereas the current study used a 5-axis CNC with jig components. In both previous studies, the resulting contour and geometry did not accurately resemble the final implant product. The use of various cutting tools and strategies to achieve precise shapes and dimensions highlights the importance of careful planning in the manufacturing process. [20][21].

Figure 5. Views of total knee replacement after machining

3D scanning physical models involves surface digitisation using Creality CR-Scan Ferret Pro brand scanners. The first step in the scanning process is using AESUB liquid. In certain parts, markers indicate pattern boundaries. Some images from various angles are obtained by rotating the physical model (fixed scan) or by moving the scanner to the desired angle (handheld rapid scan), so that the entire surface is captured as a point cloud. In this study, the scanned part was the femoral component. The scanning process is shown in Figures 6 and 8. [22]

Figure 6. Total Knee Replacement (TKR) implant scanning process using AESUB spray [23][24].

AESUB 3D Scanning Spray is designed for 3D scanners to enhance scanning. They are intended for dark-coloured objects and those that reflect light. AESUB 3D Scanning Spray has a layer thickness of 8-15 μm [23].

Figure 7. AESUB 3D Scanning Spray.

The next step is to generate a point cloud into a triangle shape; this shape most effectively follows the model profile. The final phase of this stage involves closing the former marker and black side holes with the fill hole feature in the scanner software. The result of this process is a 3D model that resembles the original shape, as seen in Figure 8. Scanning data can be exported to SOLIDWORKS software in various formats, including STL, OBJ, PLY, ASC, and P3.

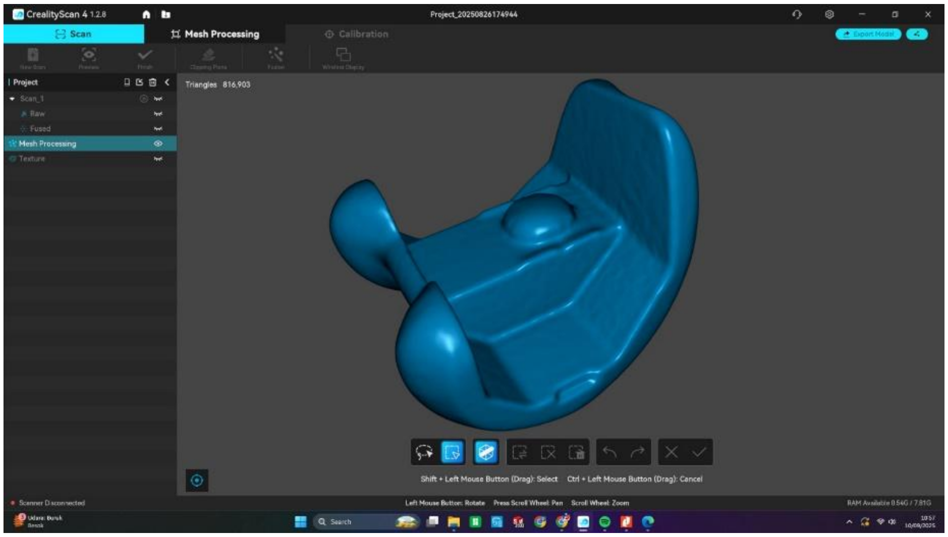


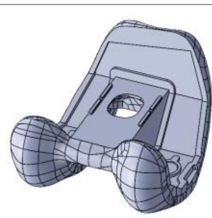
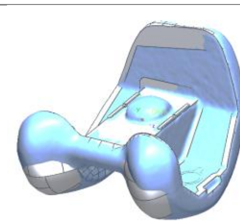
Figure 8. Femoral scanned using AESUB 3D Scanning Spray.

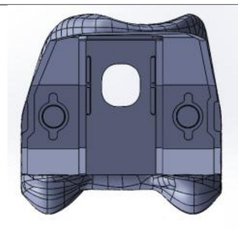
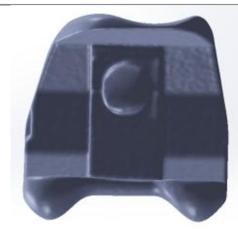
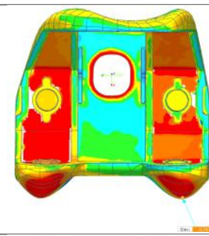
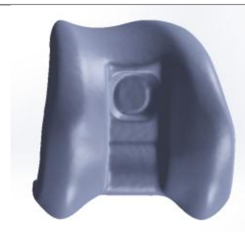
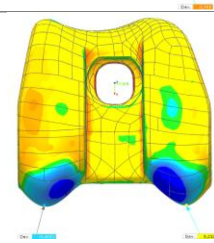
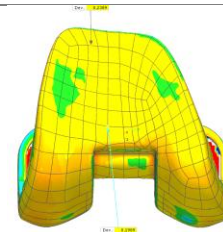
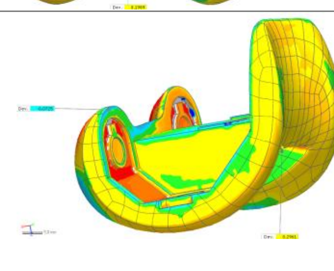
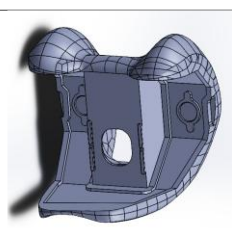
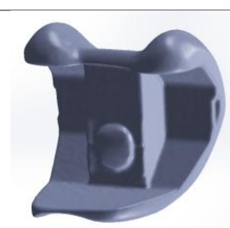
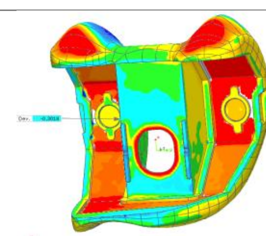
3. Results and discussions

One potential source of systematic measurement error in this study is the application of AESUB Blue scanning spray, which is necessary to capture the reflective surfaces of the metallic femoral component. According to the manufacturer's specifications, the spray forms a coating layer approximately 8-15 µm (0.008-0.015 mm) thick. However, this additional thickness is considered acceptable in orthopaedic implant manufacturing. Typical geometric profile tolerances for femoral components and similar complex orthopaedic surfaces generally range from 0.1 mm to 0.3 mm. [25]. Consequently, the maximum deviation introduced by the spray layer represents only a minor fraction (approximately 5-10%) of the total allowable tolerance band. Furthermore, the homogeneous nature of the spray coating minimizes local irregularities, ensuring that the scanned profile accurately represents the machined geometry for dimensional verification. [26][27]

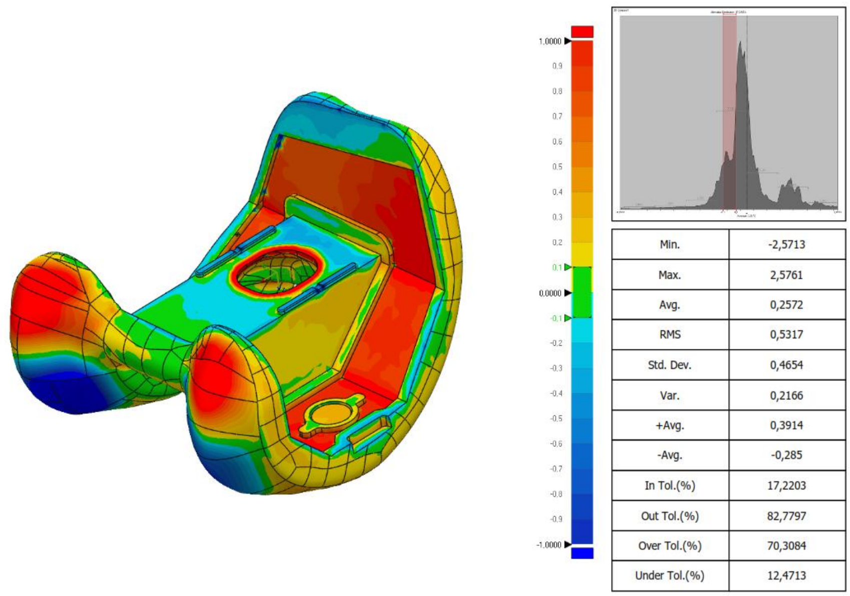
The developed 3D models were exported as STL files and analyzed with Geomagic Control X for shape validation. The process began by importing both the TKR CAD design and the TKR after CNC machining the 3D-scanned design into Geomagic. Best-fit alignment and registration were performed based on anatomical reference points. Spatial comparison was conducted using the 3D Deviation Analysis feature, which generated a color deviation map and computed quantitative parameters, including Root Mean Square (RMS) deviation and maximum absolute deviation. This analysis aimed to quantify the geometric modifications applied to the standard design and to identify significant spatial deviations, particularly in the posterior condyle region.

Table 3 TKR CAD design and TKR after CNC machining, 3D-scanned and combined with Geomagic.

Position	**TKR CAD design**	**TKR after CNC machining, 3D scanned**	**TKR CAD design and TKR after CNC machining were 3D scanned**
Initial Alignment			

Distal Femoral 0.749			
Lateral Condyles and Medial Condyles -0,4683 and 0,232			
Anterior Flange and Pattelar Groove 0,2389 and 0, 1989			
Posterior Stabiliser and Intercondylar Notch -0,0725 and 0,2961			
Stem or Central Stem -0,3018			

In the manufacturing process of high-precision medical implants such as femoral components for Total Knee Replacement (TKR), 3D Compare is the most crucial final verification stage in tolerance inspection. This advanced feature compares the three-dimensional scan data profile of the finished physical component with the reference data from the original digital design (CAD model). This comparison is conducted comprehensively in three-dimensional space, enabling detection of even minor deviations across all surfaces and contour profiles. Thus, 3D Compare serves as the final quality assurance step, ensuring that every implant produced has perfect geometric accuracy and complies with stringent tolerances, thereby supporting successful operations and patient comfort.



Min.	-2,5713
Max.	2,5761
Avg.	0,2572
RMS	0,5317
Std. Dev.	0,4654
Var.	0,2166
+Avg.	0,3914
-Avg.	-0,285
In Tol.(%)	17,2203
Out Tol.(%)	82,7797
Over Tol.(%)	70,3084
Under Tol.(%)	12,4713

Figure 9. 3D comparison of the TKR CAD design and the TKR after CNC machining.

4. **Conclusion**

This study validated a two-phase 5-axis CNC machining strategy for fabricating AISI 316L femoral components, achieving a total production cycle time of 160 minutes. The 3D scan-based dimensional verification demonstrated that the manufacturing process yielded a geometry with a global Root Mean Square (RMS) deviation of 0.5317 mm and an average positive deviation of 0.2572 mm. Higher accuracy was observed in critical functional regions, with the patellar groove exhibiting a deviation of 0.1989 mm and the condyles ranging from -0.4683 mm to 0.232 mm. Although the toolpath strategy proved effective in generating complex sculptured surfaces, spatial analysis revealed extreme deviation ranges from -2.5713 mm to +2.5761 mm, with tolerance distribution data indicating that 17.22% of the total surface area fell within strict tolerance limits. These quantitative results confirm the viability of the proposed CAM simulation workflow and highlight the need to optimize fixturing strategies further and finishing parameters to minimize dimensional discrepancies across the remaining 82.78% of the surface area.

Declaration of AI and AI assisted technologies in the writing process

During the preparation of this work, the author(s) used Gemini in order to improve the readability and language flow of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors thank the Indonesia Endowment Fund for Education Agency and the National Research and Innovation Agency for research funding under RIIM grants of numbers: 156/IV/KS/11/2023 and 353/LPPM/UWH/XI/2023.

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