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MASTER'S THESIS SUMMARY

# Detection of the centroid of femoral condyles with computer vision and artificial intelligence

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**Abstract.** This work presents a method based on computer vision and medical image processing for the automated detection of the femoral condyle centroid in total knee arthroplasty (TKA). DICOM image preprocessing is implemented, followed by femoral condyle segmentation, edge detection using the Canny operator, and centroid calculation through the selection of four key anatomical points. This technique reduces variability in manual detection, improving prosthetic implant alignment and optimizing surgical planning. The results demonstrate that centroid detection is accurate and reproducible, enabling integration into surgical navigation systems and robotic surgery. This development represents an advancement in artificial intelligence (AI) for orthopedic surgery, enhancing procedural accuracy and reducing surgical times.

**Keywords:** Computer vision, total knee arthroplasty (TKA), medical image processing, centroid detection, surgical planning.

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## 1 Introduction

The development of this project aims to enhance the accuracy of prosthesis placement in knee surgeries through the use of computer vision and artificial intelligence. Total knee arthroplasty (TKA) is one of the most common procedures due to its efficacy in treating advanced knee osteoarthritis within the orthopedic field, particularly in elderly patients, where post-surgical complications such as joint infections and painless solid arthrodesis have been identified (Morán Lorenzo, 2022). However, despite its success, conventional methods for managing the femoral condyle centroid during alignment and placement pose challenges in achieving precise identification of the femoral condyle centroid. This impacts the long-term stability and reliability of the prosthesis, which are neither cost-effective nor beneficial in terms of health and economic outcomes for patients.

Recent studies have shown that knee joint replacement surgery significantly improves patients' quality of life, with a 100% reduction in pain intensity and a decreased risk of falls (Amparan et al., 2022). However, achieving accuracy in femoral prosthesis alignment remains a significant challenge due to anatomical variations among individual patients.

Currently, orthopedic robotic systems designed to be teleoperated by surgeons have been developed, enhancing surgical planning, reducing the frequency of medical errors, and optimizing alignment. These systems provide surgeons with precise accuracy in the placement of femoral prosthetic components for total knee arthroplasty (TKA) (García Pérez & Martín Hernández, 2022). Nevertheless, their high costs remain a significant drawback, limiting accessibility. Additionally, these systems do not fully resolve the challenge of femoral condyle centroid detection. Therefore, integrating computer vision and artificial intelligence with deep learning models could complement robotic surgery to improve clinical outcomes.

On the other hand, prosthesis misalignment can result in a significant clinical impact due to the occurrence of early postoperative complications, such as persistent pain, joint instability, implant wear, increased risk of falls, and higher healthcare and medical costs. By addressing these issues, robotic systems may reduce such complications and offset their costs through more precise alignment. However, the high equipment cost remains the primary barrier to implementing this technology in clinical units.

This study proposes the development of a system that, using DICOM medical images from magnetic resonance imaging (MRI), enables precise detection of the femoral condyle centroid through image processing techniques, computer vision, and artificial intelligence with deep learning. This approach aims to improve surgical accuracy by reducing variability in manual detection, optimize the prosthesis alignment process in total knee arthroplasties (TKA), enhance clinical outcomes, and lower long-term costs.

### 1.1 Motivations

Total knee arthroplasty (TKA) is a surgical procedure in which the damaged knee joint is replaced with an artificial prosthesis. It is widely used in patients with advanced osteoarthritis or other degenerative knee conditions (Buñay Azas, 2024). However, incorrect prosthesis alignment remains one of the leading causes of surgical failure, which can result in complications such as accelerated implant wear due to joint instability, necessitating surgical revisions and causing adverse health outcomes for patients (Torres Casado & Ruiz Suárez, 2021). To improve the accuracy of prosthetic implant placement in TKA, robotic surgery systems and computer-assisted navigation technologies have been developed, demonstrating reduced human error and improved postoperative outcomes (Moncada Granda & Fabián Gerardo, 2023). Nonetheless, the high costs associated with acquiring and maintaining specialized equipment pose a significant barrier to implementing these technologies in clinical practice.

The proposed system enables automated detection of the femoral condyle centroid through deep learning and medical image processing of DICOM-formatted magnetic resonance imaging (MRI) scans, enhancing prosthetic alignment accuracy and reducing the surgeon's reliance on subjective decision-making. Artificial intelligence applied to surgical planning not only optimizes hospital time and resources but also allows for integration into robotic surgery and computer-assisted navigation systems, enabling more precise diagnoses and personalized procedures.

Furthermore, this work aligns with the United Nations 2030 Agenda for Sustainable Development, contributing to SDG 3 (Good Health and Well-being) and SDG 9 (Industry, Innovation, and Infrastructure) by enhancing surgical efficiency, reducing postoperative complications, and lowering the environmental impact of the healthcare sector. At the national level, the project is in line with Mexico's PRONACES (National Strategic Programs) in Health, Science, Technology, Innovation, and Well-being, promoting the development of AI-based medical tools that optimize surgical precision and improve patients' quality of life.

For this reason, the development of a model for automated femoral centroid detection is proposed, using advanced medical image segmentation techniques and convolutional neural networks (CNNs). The application of this innovative approach can optimize surgical planning for total knee arthroplasty (TKA), providing a more precise and accessible method for prosthetic alignment.

## 1.2 Description of the research problem

Recent studies have revealed that approximately 15% of patients undergoing total knee arthroplasty (TKA) exhibit femoral prosthesis malposition, with an average external rotation deviation of ±2.2°. This deviation can compromise prosthesis alignment and, in the long term, its functionality (Fiallo Rodríguez et al., 2024).

Despite improvements in surgical techniques over the years, the localization of the femoral condyle centroid remains heavily reliant on the surgeon's skill and experience. The manual nature of this process introduces variability and subjectivity during prosthesis alignment, compromising surgical precision (León Muñoz, 2021). The primary challenges include:

- **Variability in centroid identification**: Differences in surgeon experience may lead to alignment errors.
- **Difficulty in medical imaging detection**: The quality of magnetic resonance imaging (MRI) or computed tomography (CT) scans influences the accuracy of centroid detection.
- **Impact on prosthetic alignment**: Errors in centroid localization can compromise prosthesis alignment, increasing stress on suboptimal implant regions and accelerating component wear, which raises the risk of surgical revisions (Yáñez Siller et al., 2021).

Given that alignment precision in total knee arthroplasty (TKA) is critical for prosthesis stability, implementing an artificial intelligence (AI)-based system can enhance femoral condyle centroid detection, reducing variability associated with manual evaluation and improving surgical planning (Moya et al., 2022). An AI-driven model could:

- Reduce variability in centroid identification, ensuring a more precise anatomical reference.
- Optimize the prosthetic alignment process, lowering the likelihood of malrotation.
- Integrate with robotic surgery and computer-assisted navigation systems, enhancing preoperative planning and procedure execution.

The lack of a reliable and automated method to detect the femoral condyle centroid represents a limitation in the surgical precision of total knee arthroplasty (TKA). Therefore, the development of an artificial intelligence and computer vision-based model would not only optimize surgical planning and prosthesis alignment but also help reduce postoperative complications and improve long-term clinical outcomes.

## 1.3 Medical and Legal Standards and Regulations

**Regulation of Medical Devices in Mexico (COFEPRIS).**
In Mexico, the Federal Commission for the Protection against Sanitary Risks (COFEPRIS) regulates the use and development of medical devices through regulations that ensure their safety, quality, and efficacy in clinical settings. In the context of this project, it is essential to consider the applicable regulations for medical systems based on computer vision and artificial intelligence, ensuring compliance for a safe and validated development.

**NOM-137-SSA1-2008:** Labeling of Medical Devices.

- Regulates the labeling and information that medical devices must contain for commercialization and clinical use.
- Ensures that medical devices meet identification, traceability, and safety requirements.
- May apply if the developed software is integrated into a physical device that requires certification.

(Secretaría de Salud, 2008)

**NOM-240-SSA1-2012:** Installation and Operation of Technovigilance.

- Regulates the monitoring and control of medical devices in clinical use, including digital systems.
- Ensures that medical image processing software complies with safety and continuous monitoring standards in hospitals.

- This regulation is essential to ensure that artificial intelligence systems applied in orthopedic surgery meet the required monitoring and safety standards.

(Secretaría de Salud, 2012)

**NOM NOM-241-SSA1-2021:** Good Manufacturing Practices for Medical Devices.

- Establishes quality requirements for the development of medical software.
- Regulates the design, development, production, and control of technologies used in the healthcare sector.
- Applicable if the computer vision-based system is used in technology-assisted surgeries.

(Secretaría de Salud, 2021)

Compliance with the regulations established by COFEPRIS, particularly **NOM-137-SSA1-2008, NOM-240-SSA1-2012, and NOM-241-SSA1-2021**, related to the **"health regulation of national health systems,"** is essential in ensuring that a femoral condyle centroid detection system meets the minimum safety, validation, and operability requirements necessary for a surgical environment. These regulations provide a framework for the development of safe and efficient medical software.

## 1.4 Objectives of the thesis

**General Objective:**

Develop a system based on computer vision and digital image processing for the precise detection of the femoral condyle centroid, aiming to optimize prosthetic implant placement in total knee arthroplasty surgeries. The system will integrate segmentation techniques, feature extraction, and machine learning, supported by a mathematical model that enhances centroid calculation accuracy, facilitating its application in a surgical environment.

**Specific Objectives:**

- Analyze the surgical procedure for knee prosthesis placement to identify the challenges associated with detecting the femoral condyle centroid, documenting the limitations of the manual process and defining technical requirements for its automation.
- Select and structure a dataset of DICOM medical images of the femur for system training, ensuring data quality through preprocessing, segmentation, and image validation techniques.
- Develop a segmentation algorithm and femoral condyle contour detection method to extract relevant features, using image processing and deep learning techniques to enable the correct identification of the region of interest.
- Train and evaluate artificial intelligence models for the automatic detection of the femoral condyle centroid, integrating a mathematical model that optimizes centroid calculation accuracy to improve surgical planning and alignment.

## 1.5 Brief description of the contribution of the thesis

This study proposes an innovative method based on computer vision and artificial intelligence (AI) for the automated detection of the femoral condyle centroid, a task currently performed manually by surgeons during total knee arthroplasty (TKA) procedures. By leveraging DICOM medical image processing, segmentation techniques, edge detection, and machine learning, the developed system aims to enhance the precision of prosthetic placement in knee surgery. This approach reduces variability in centroid detection and optimizes surgical planning through the proposed method.

The most significant contribution of this research lies in the application of an AI architecture trained on processed magnetic resonance imaging (MRI) scans. This architecture not only detects the femoral condyle contour but also enables automatic and accurate identification of the centroid. By utilizing the centroid as predefined variables, the system facilitates the surgical act of joint replacement through precise internal capture of critical anatomical landmarks. Thus, this work demonstrates how AI can significantly advance traditional methods in orthopedic surgery.

Additionally, this study integrates a mathematical model to calculate the centroid based on characteristic anatomical points of the femoral condyle, providing an objective assessment for optimal prosthetic implant positioning. Once validated, this system could be further implemented as a medical software enhancement or integrated into surgical navigation systems to streamline its use in TKA procedures, thereby enhancing surgical efficacy. We anticipate that this work will serve as a cornerstone for the integration of AI into orthopedic technological development, offering a precise and accessible pathway for preoperative planning in total knee arthroplasty.

## Background (State of the Art)

There are various studies related to the project that will be conducted and will serve as a guide for complementing the thesis topic. This includes research from different types of sources, including the reviewed articles.

1.6 Applications of Computer Vision in Orthopedic Surgical Procedures:

The research team of Avila-Tómas (Avila-Tomás et al., 2020) recognized this important aspect, initially using it as a reference point in navigated revision knee prosthesis surgery programs. A couple of years later, it was incorporated into navigation programs for primary knee surgery. Total knee arthroplasty (TKA) can lead to joint instability, anterior knee pain, limited range of motion, and joint stiffness.

The author Vaccarelli Miguez (Vaccarelli Miguez, 2020) aimed to rethink the development of courses that, until now, did not incorporate technological devices among their resources. This initiative was based not only on the global advancement of technologies but also on health sciences. The initial results relate to training across different settings and maximizing the time professionals can dedicate to their education. Updating courses also means updating and better preparing professionals for an increasingly demanding job market.

The study by Romero-Medina (Romero-Medina et al., 2021) highlighted that navigated total knee arthroplasty (TKA-N) is a continuously growing surgical technique due to its precision and effectiveness. According to the authors, this technique uses a computer-guided system that provides real-time information about the knee before cutting, including details on alignment, lesion depth, and capsuloligamentous stability. They stated that this system helps surgeons perform bone cuts with millimeter precision and balance the ligaments, ensuring proper alignment and stability throughout the knee's full range of motion.

The research group of Berebichez-Fridman (Berebichez-Fridman et al., 2021) conducted a search for the most relevant and recent evidence regarding the use of tranexamic acid in Orthopedics and Traumatology, including its indications, contraindications, and adverse effects. Their findings revealed numerous applications, particularly in knee and hip arthroplasty, spinal surgery, and trauma care. Multiple administration routes and dosing regimens exist, all proving effective; however, the most optimal administration route and dosage have yet to be standardized. They concluded that tranexamic acid is a safe and effective drug for reducing perioperative bleeding.

The authors Bustamante and Correa (Bustamante & Correa, 2023) defined artificial intelligence (AI) as a field of study aimed at developing systems capable of performing tasks traditionally requiring human intelligence. These tasks include reasoning, learning, visual perception, speech recognition, decision-making, and language translation. Essentially, the goal of AI is to emulate human cognitive abilities in machines.

The research team of Fiallo Rodríguez (Fiallo Rodríguez et al., 2024) demonstrated that total knee arthroplasty (TKA) is recommended for patients with significant pain, severe functional limitation, and severe joint damage when other treatments are ineffective. However, the author pointed out that achieving the correct rotation of the femoral component is challenging in both conventional TKA and navigation-assisted TKA. Robot-assisted TKA, such as the All Burr technique, has improved placement precision, reducing coronal misalignment from 3° to less than 1.24° and sagittal malpositioning to less than 1°.

1.7 Segmentation Techniques and Detection of Anatomical Features in Medical Images:

The authors Vasquez and Claros (Vasquez & Claros, 2020) implemented a Support Vector Machine (SVM) classifier, based on the Kellgren-Lawrence (KL) classification method, using X-ray (XR) images to assist trauma specialists in diagnosing the degree of knee osteoarthritis (OA) according to the aforementioned classification. Their study was conducted on patients from the Orthopedics and Traumatology Department at Clínica Medilaser in Neiva, treated between June and August 2020. Based on previous results, they opted to use an RBF Kernel in their custom-built database, achieving an AUC of 91%, which represented a significant improvement over previous results.

The research team of Ávila-Tomás (Avila-Tomás et al., 2020) explained that artificial intelligence (AI) consists of a series of sufficiently trained logical algorithms, enabling machines to make decisions in specific cases based on general rules. This approach focuses on designing computational tools that simulate human intelligence processes, including learning, reasoning, and self-correction. According to the authors, autonomous machines, through various algorithms, can make decisions efficiently.

In the following study, the authors Carranza-Delgado (Carranza-Delgado et al., 2021) focused on key methods for evaluating structural damage in osteoarthritis patients. Conventional radiography is the most well-known and accessible method, but it does not assess non-calcified tissues. Magnetic resonance imaging (MRI) visualizes both intra-articular and extra-articular soft tissues, although it is expensive and less available. Medical imaging plays a crucial role in classifying osteoarthritis severity and assessing treatment effectiveness. While simple radiographs are the most accessible for joint evaluation, micro-focused radiographs provide more precise assessments.

The author León Muñoz (León Muñoz, 2021) analyzed the advantages and disadvantages of imaging instruments. Due to the broad scope of the topic, the study focused on specific aspects, compiling scientific articles within the present thesis. Additionally, the study examined the degree of alteration introduced by weight-bearing and non-weight-bearing computed tomography (CT) imaging acquisition. The results indicated that 3D models underestimate the degree of knee joint deformity, both in varus and valgus, when compared to full-weight-bearing radiographic studies of the entire limb.

### 1.8 Impact of Extra-Articular Diseases, Anatomical Deformities, and Clinical Guidelines on Surgical Planning

The study by García Alvarado (García Alvarado, 2023) highlighted that computer-aided diagnosis (CAD) is a non-invasive diagnostic tool that aids in the early detection of potentially life-threatening diseases through medical image processing techniques. According to the author, this type of tool provides fast and highly accurate results, enabling physicians to make better strategic and treatment planning decisions. Furthermore, workflow optimization can be achieved by automating computed tomography (CT) image scanning routines, requiring minimal to no human intervention.

The research team of Salazar-López (Salazar-Lopez J.N. et al., 2023) successfully achieved postoperative coronal alignment. Robotic-assisted surgery ensures functional alignment, defined as a hip-knee-ankle angle of 0°. However, since robot-assisted surgery is not available for all patients, it is necessary to include full-body weight-bearing anterior-posterior (AP) radiographs (front-to-back view) from hip to ankle in preoperative planning to achieve safe-zone alignment.

The research group of Palestino-Lara (Palestino-Lara et al., 2024) pointed out that inadequate postoperative pain relief can prolong recovery time, increase hospitalization days, and even lead to possible readmission. According to the authors, navigated total knee arthroplasty (TKA-N) is one of the most advanced procedures for treating knee osteoarthritis. For this procedure to be successful, it requires proper patient selection, detailed pre-surgical planning, accurate implant sizing, appropriate postoperative follow-up, early mobility, and effective physical rehabilitation.

## 2 Proposed Solution Approach

### 2.1 DICOM Image Preprocessing:

To ensure adequate image quality and facilitate segmentation, the following preprocessing techniques are implemented:

- Conversion of the DICOM image into a numerical matrix using the SimpleITK library.
- Normalization of the image to an 8-bit scale (0-255) to enhance contrast and visualization.
- Threshold-based segmentation, setting minimum and maximum threshold values to highlight regions of interest.
- Noise removal, applying morphological filters to eliminate small objects and fill gaps in the segmented image.

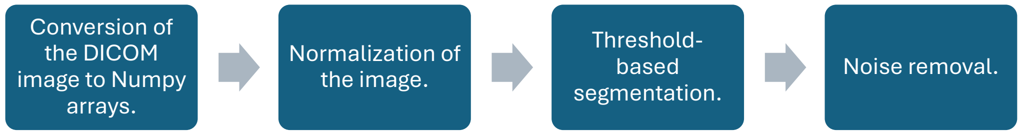


Fig. 1 Preprocessing Pipeline.

This set of techniques helps reduce image noise artifacts, ensuring adequate clarity for the next stage.

2.2 Edge Detection Using the Canny Operator:

Once the image has been preprocessed, the Canny operator is applied to detect the edges of the anatomical structure. This method is justified due to its ability to:

- Highlight the most significant contours with high precision.
- Reduce false positives by incorporating a non-maximum suppression process.
- Adjust sensitivity through smoothing and thresholding parameters.

The detected edges are represented in a binary image, enabling the identification of the femoral condyle contour. Subsequently, the most prominent contour is extracted and stored in an image with a transparent background for further analysis.

2.3 Centroid Calculation Through the Selection of Anatomical Points:

After edge detection and femoral condyle segmentation, the next step is to calculate its anatomical centroid. This requires selecting four key points, which correspond to relevant anatomical structures:

- Two points on the posterior condylar axis, representing the longest horizontal line of the femoral condyle.
- Two points on the transepicondylar axis, forming the shortest vertical line of the condyle.

These points are manually selected by the user through a graphical interface, ensuring precise positioning on the segmented condyle image.

Mathematical Method for Centroid Calculation For a set of $N$ points $(xi, yi)$, the centroid is calculated using the following formula:

$$\mathcal{X}_c = \frac{\sum_{i=1}^{N} x_i}{N}, \mathcal{Y}_c = \frac{\sum_{i=1}^{N} y_i}{N}$$

Source: Hibbeler, R. C. (2014). Statics and Mechanics of Materials.

- $X_i$, $Y_i$: Coordinates of the contour points.
- $N$ : Total number of points in the contour.
- $X_c$, $Y_c$ : Centroid coordinates.

The selection of the four points corresponding to the posterior condylar axis and the transepicondylar axis is crucial to ensuring precise centroid alignment in total knee arthroplasty (TKA). These points must be selected in a specific order, following the correct anatomical sequence, as shown in Illustration 1. Their selection is based on the following criteria:

1. **Lateral femoral condyle (left) and medial femoral condyle (right**).
    - These points represent the extremes of the posterior condylar axis, which is a key reference for prosthesis alignment.
    - Variability in the identification of these points can affect the rotation of the femoral component, impacting postoperative prosthesis stability.
2. **Central region of the distal femur (Superior central).**

  - Represents a stable reference point in the bony geometry of the distal femur, improving centroid calculation accuracy in irregular structures.
  - A key point in load distribution and prosthesis alignment.

3. **Intercondylar region of the cruciate ligaments (Central middle).**
  - Located at the center of the knee, where the main ligaments (anterior and posterior cruciate ligaments) intersect.
  - Its selection provides a reliable anatomical reference to define the transepicondylar axis, which is essential for prosthetic alignment.

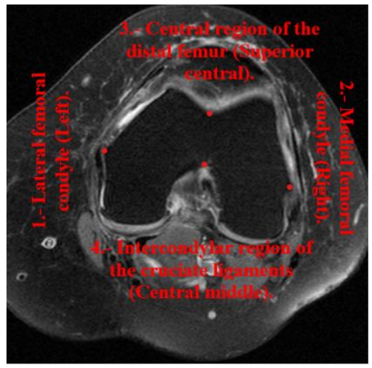


Fig. 2: Location of the four key anatomical points for centroid calculation in TKA.

### 2.4 Advantages and Limitations of the Proposed Approach

This method is well-suited for medical image processing due to its ability to enhance segmentation and highlight anatomical structures of interest. Additionally, since it is based on classical processing techniques, it allows for efficient implementation without requiring large volumes of training data or intensive computation. However, future research should consider integrating more advanced models, such as deep learning, to improve segmentation accuracy and system adaptability in images with complex variations.

**Advantages:**

- Enhances image quality through normalization and noise reduction.
- Enables segmentation of bone structures without requiring manual intervention.
- Canny edge detection is efficient and computationally inexpensive.

**Limitations:**

- Threshold-based segmentation depends on image quality and optimal parameter selection.
- Edge detection may be affected by variations in image intensity.
- Adaptive methods or machine learning are not considered to improve segmentation in complex cases.

## 3 Experimental results

This section presents the results obtained in the implementation of femoral condyle centroid detection using image processing and computer vision techniques. Through a systematic series of steps, the femoral condyle was successfully segmented, its edge detected, and the centroid accurately calculated.

### 3.1.1 Femoral Condyle Segmentation:

The first step in medical image processing involves normalizing and filtering the DICOM image, converting it to grayscale, and adjusting its contrast to improve the visibility of relevant anatomical structures. Illustration 3 presents the pipeline followed for image preprocessing, highlighting the normalization, filtering, and conversion stages into a binary format.

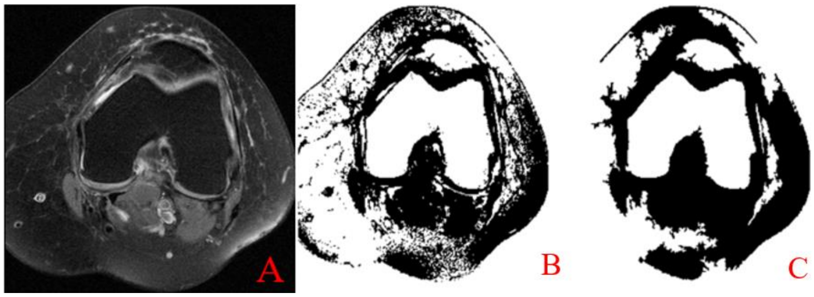

Fig. 3: Results of Femoral Condyle Segmentation.

**Description:**

A. Original grayscale DICOM image.
B. Initial segmentation result of the femoral condyle using thresholding.
C. Refined segmentation after noise removal and morphological filtering.

3.1.2 Detection of the Femoral Condyle Contour Using the Canny Operator:

Subsequently, the **Canny operator** was applied to detect the edges of the **femoral condyle**. **Figure 4** illustrates how the **condyle contour** was extracted, highlighted in **yellow**, allowing for a more precise identification of the **region of interest**.

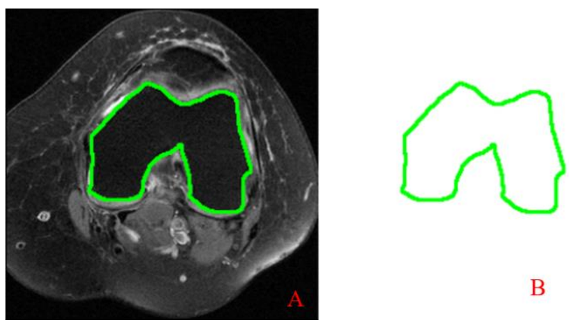

Fig. 4: Extraction of the Femoral Condyle Contour

**Description:**

A. Detected contour highlighted in green over the MRI image.
B. Extracted contour on a white background for independent analysis.

3.1.3 Centroid Calculation Through the Selection of Anatomical Points:

To obtain the anatomical centroid, four key points were selected along the condyle contour, corresponding to the posterior condylar and transepicondylar axes. Figure 5 illustrates the three stages of the process:

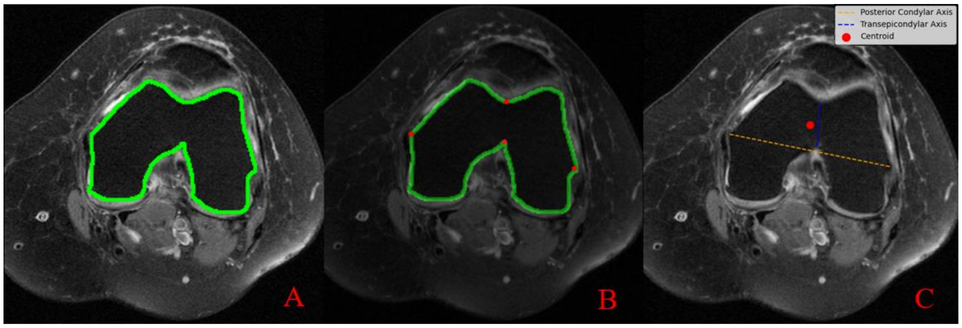

Fig. 5: Centroid detection process based on anatomical coordinates.

**Description:**

A. Detected femoral condyle contour in the MRI image.
B. Manual selection of the four key anatomical points along the contour.
C. Final centroid calculation with reference axes (posterior condylar and transepicondylar).

# 4 Conclusions

This study introduces an innovative method based on computer vision and artificial intelligence (AI) for the automated detection of the femoral condyle centroid. The method is manually implemented by surgeons during total knee arthroplasty (TKA). The proposed system integrates DICOM medical image processing, segmentation techniques, edge detection, and machine learning within a custom-developed operating system to enhance the precision of prosthetic implant placement in knee surgery. By reducing variability in centroid identification, this system optimizes surgical planning. The primary contribution of this work is an artificial intelligence (AI) architecture trained on processed magnetic resonance imaging (MRI) scans, which accurately delineates the condylar contour. This architecture can also be applied to automatically and precisely identify the centroid within the surgical field environment.

Furthermore, preprocessing and edge detection methods in medical image processing are critical for diagnostic assistance and automated anatomical structure analysis. This study reviewed preprocessing techniques and edge detection operators for DICOM images, emphasizing the importance of pixel scaling, normalization, segmentation, and noise reduction to improve image quality. The Canny edge detector proved highly effective for contour extraction, enabling straightforward condyle detection in magnetic resonance imaging (MRI) scans. In conclusion, preprocessing and edge detection techniques are essential for robust segmentation in medical imaging. Their proper implementation not only enhances image visualization but also advances the potential for future automation in surgical precision.

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