

KINEMATICS COMPARISON TOOL FOR ALIGNMENT ADJUSTING IN TOTAL KNEE REPLACEMENT SURGICAL PLANNING

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Abstract—This study is to develop a flexible kinematic model for pre-operative training and planning purposes in the Total Knee Replacement surgery (TKR). The kinematic model is used for predicting and demonstrating the post-operative results with an approach based on 1) mechanical axis alignment, 2) intramedullary canal's axis, 3) anatomical landmarks (e.g. medial and lateral femoral condyle, medial and lateral femoral epicondyle and tibia tuberosity). The study is separated into two stages, which are: kinematic model development and TKR simulation to show the result of error assessment. The study compares simulated results from different TKR cases. The TKR cases include Case 1: error in orientation about intramedullary canal's axis, Case 2: error in orientation about patella's axis, and Case 3: combination error in orientation about both intramedullary canal's axis and patella's axis using Euler angle. The results of this study are accepted to be used for TKR surgical training and planning, based on highly skilful TKR surgeons' comments. The kinematic model also can accommodate various knee implants due to its kinematic algorithm and input parameter system. The study is a part of research on "TKR surgical navigation system with high flexibility and low learning curve."

Keywords-Total Knee Replacement; Kinematic analysis; Computer-Integrated Surgery; Simulation; Mechanical axis alignment

I. INTRODUCTION

The purpose of this study is to develop a 3-Dimensional kinematic model of the mechanical axis alignment to correct the placement of knee implant. That could allow us to predict the required knee prosthesis' parameters, intending to simulate its kinematics during knee flexion movement. The kinematic model is used for demonstrating the post-operative results with an approach based on 1) mechanical axis alignment, 2) intramedullary canal's axis, 3) anatomical landmarks (e.g. medial and lateral femoral condyle, medial and lateral femoral epicondyle and tibia tuberosity). The study is separated into two stages, which are: kinematic model development and TKR simulation show result of error assessment. The study compares simulate results from TKR cases. The TKR cases include Case 1: error in orientation about intramedullary canal's axis, Case 2: error in orientation about patella's axis, and Case 3: combination error in orientation about both intramedullary canal's axis and patella's axis using Euler angle.

II. BACKGROUND

Total Knee Replacement (TKR) is an orthopedic surgery to treat the patient with a painful knee. This may cause by arthritis; such as, osteoarthritis, rheumatoid arthritis, and traumatic arthritis. TKR procedure replaces the damaged bone and cartilage at the knee joint with three major components of prosthesis to reach the goal as to restore the normal mechanical axis alignment of leg and patient able to walk normally. Fig.1 shows the normal mechanical axis alignment in frontal and sagittal view. The normal mechanical axis alignment is defined as a line that passes and through the center of the femoral head, the center of the knee and the center of the ankle [1]. The appropriate alignment is the necessary factor to provide a long life of the prosthesis, pain free, good kinematics of leg motion and avoid revision operation [2].

TKR standard procedure needs to resurface the knee bones to fit with the geometry shape of prosthesis. Fig. 2 shows the knee prosthesis components. To resurface the knee bone, firstly, the distal of femur bone is cut by mounting the series of jigs and fixtures to guide the cutting tool. Then, the proximal of tibia bone is cut in the similar way, after that the patella is the last one. The conventional procedure needs high skill and experience of the surgeon according to it is base on knee anatomical landmarks therefore needs good decision during perform the task. Since, the critical step is the process to locate the first cutting guide is called intramedullary rod to resurface the first plane on femur bone. This plane will be marked as reference for the remaining planes, and the conventional procedure does not have method to certify the accuracy of cutting plane for each step. These may result in a accumulate error leading to dislocation of prosthesis.

Currently, TKR with kinematics navigation comes to role in this field, which has benefit than conventional procedure [3]. The TKR navigation is the one type of Computer-Integrated Surgery (CIS) that assist the surgeons to perform their work more accurately by guiding, able to monitor and able to collect the data feedback to check the accuracy step by step. That is why the position and orientation of prosthesis are improved after surgery by using TKR navigation system.

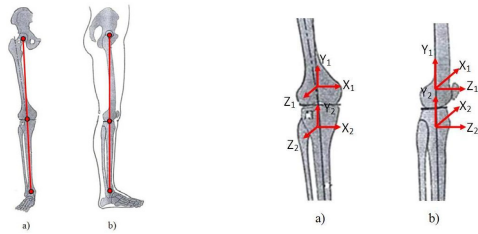


Fig. 1 Normal mechanical axis alignment and Kinematics of normal knee a) frontal view b) sagittal view

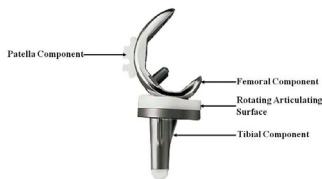


Fig. 2 Knee prosthesis components manufactured by Johnson & Johnson company

III. MATERIALS AND METHODS

A. System Overview

We have developed a CIS System [4], the project is TKR surgical navigation system with high flexibility and low learning curve, it is base on numerical modeling which can flexible to any prosthesis's models and sizes. The overall system are composed of four parts; 1) Pre-modeling of knee and prosthesis kinematics, 2) Real-time data acquisition processes, 3) Optical tracking system, 4) Graphic User Interface (GUI). Fig.3 shows diagram of the overall system.

In part of Pre-modeling of knee and prosthesis kinematics is the kinematics analysis and algorithms development, which generate the workspace, path planning and flexible kinematics model of cutting shapes on femur and tibia to fit with various popular knee prosthesis.

So, this CIS system is not base on data storage. The algorithm part will retrieve the information of prosthesis dimensions from part 2: the real-time data acquisition process. Then, the algorithm will generate the prosthesis model and path planning and communicate to the surgeon via GUI during perform the task. The optical tracking system is used for indicate the pose (position and orientation) of knee bones and surgical instruments to display the relationship between each object in the work space.

B. Kinematics Analysis

Kinematics is the science of motion which treats motion without regard to the force that causes it [5]. These would involve with the description to specify attributes of various objects. There are positions, orientations and frame is an entity which contains both position and orientations. In this section, describes the kinematics analysis of two objectives which are knee kinematics and knee prosthesis kinematics.

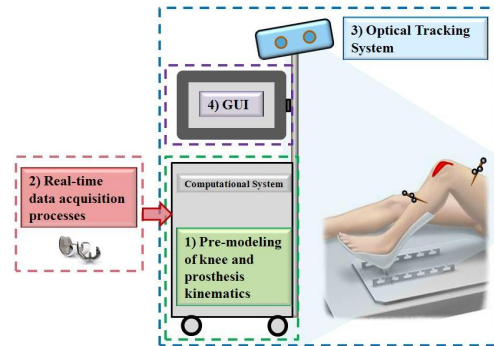


Fig. 3 diagram of the TKR surgical navigation system with high flexibility and low learning curve

1) *Knee Kinematics Analysis*: The human knee is the largest and the most complex joint in the body, which is the interaction between three bones. There are patella, femur and tibia that can be clarified into two structure of joint motion: the tibio-femoral joint (between tibia and femur), the patello-femoral joint (between patella and femur). The greatest range of motion of knee appears in the sagittal plane is occurred by tibio-femoral joint, where the range from full extension to full flexion of the knee from 0 to approximately 140 degrees [6]. In the knee kinematics analysis section, we studied the kinematics in 3-Dimensional (3D) of the normal knee, and analyze the kinematics of implanted knee.

To describe the relative motion between two rigid bodies (femur and tibia) in 3D. Two Cartesian coordinate systems were assigned to each bone as the bone's representative frame, the femur's frame was fixed as the reference body to tibia, while tibia move relatively. Fig. 1 shows an illustration of kinematics of normal knee. Firstly, the sagittal plane was considered, the flexion-extension in the tibio-femoral joint of normal knee is similar as tibia rotates about a revolute joint or about X-axis. The articular surface between circular surface of femoral condyle and flat surface of tibia cause the sliding motion (translation along Z-axis) during knee flexion but not much because the restriction of the anterior and posterior cruciate ligaments. In front plane, medial-lateral translation (translation along X-axis) and upper-lower translation (translation along Y-axis) show a few displacement because the restriction of medial and lateral collateral ligament, and also abduction-adduction (rotation about Z-axis) in a fully extended knee almost no abduction or adduction. In transverse plane, there is internal-external rotation of tibia (rotation about Y-axis) during knee flexion (rotation about X-axis) because the medial femoral condyle is longer than the lateral femoral condyle.

In the study kinematics of total knee replacement systems reported that the implanted knee kinematics are not return normal characteristic to those of the normal knee, which depending on the prostheses models [7-10]. Therefore, the main goal of the TKR surgery is to restores the normal mechanical axis and to treats the disease. For that reason this work has developed a numeric model for knee kinematics after TKR surgery to simulate the dislocation of prosthesis

that will cause the abnormal mechanical axis of the knee compare to the proper implantation that will returns the normal mechanical axis for the knee.

To demonstrate the kinematics of implanted knee, three Cartesian coordinate systems was assigned to locate at the center of hip, center of knee and center of ankle to represent the mechanical axis. The characteristic of each frame coordinate can be described by homogeneous transform matrix H . It can be regarded purely as a construction used to cast the rotation and translation of the general transform into a single matrix form. Where the rotation describes the orientation and the translation describes the position.

At the beginning of analysis, hip is assigned to be fixed as base reference. Then knee's frame is move relative to hip, the description of knee's frame relative to hip's frame is

$${}^{Hip}_{Knee}H = \begin{bmatrix} {}^{Hip}_{Knee}R & {}^{Hip}_{Knee}\bar{P} \\ \hline 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Where vector P is the displacement along Y-axis equal to length of femur (L_f)

$${}^{Hip}_{Knee}\bar{P} = \begin{bmatrix} x \\ y - L_f \\ z \end{bmatrix} \quad (2)$$

Here, R is an orthogonal matrix will represent the orientation of the femoral implant. So the parameter of R is always described by three successive rotations about the coordinate axes. The sequence of rotations was chosen to be the orientation of prosthesis first, after that flexion path motion on tibia will represent the prosthesis orientation. It can be described by Euler angles, start with knee's frame. Then rotate it about X-axis by an angle θ_x , then rotate about Y-axis by an angle θ_y , and the rotate about Z-axis by an angle θ_z . Then the rotation matrix takes on the familiar form of planar rotations:

$$\begin{aligned} R_x(\theta) &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\theta & -s\theta \\ 0 & s\theta & c\theta \end{bmatrix} \\ R_y(\theta) &= \begin{bmatrix} c\theta & 0 & s\theta \\ 0 & 1 & 0 \\ -s\theta & 0 & c\theta \end{bmatrix} \\ R_z(\theta) &= \begin{bmatrix} c\theta & -s\theta & 0 \\ s\theta & c\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{aligned} \quad (3)$$

For angle θ_x, θ_y and θ_z , abbreviating $\sin(\theta_x) = s\theta_x, \cos(\theta_x) = c\theta_x$ and so on, rotation matrix R is define as

$${}^{Hip}_{Knee}R = R_x(\theta_x)R_y(\theta_y)R_z(\theta_z)$$

$$= \begin{bmatrix} c\theta_x c\theta_y & c\theta_x s\theta_y s\theta_z - s\theta_x c\theta_z & c\theta_x s\theta_y c\theta_z + s\theta_x s\theta_z \\ s\theta_x c\theta_y & s\theta_x s\theta_y s\theta_z + c\theta_x c\theta_z & s\theta_x s\theta_y c\theta_z + c\theta_x s\theta_z \\ -s\theta_y & c\theta_y s\theta_z & c\theta_y c\theta_z \end{bmatrix} \quad (4)$$

Then, the ankle frame can be defined in the similar way as

$${}^{Knee}_{Ankle}H = \begin{bmatrix} I_3 & {}^{Knee}_{Ankle}\bar{P} \\ \hline 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

Where vector P is the displacement along Y-axis equal to length of Tibia in the same way as femur length, and I is an identity matrix setup here since the ankle was no rotation respect to the knee.

$${}^{Knee}_{Ankle}\bar{P} = \begin{bmatrix} x \\ y - L_t \\ z \end{bmatrix} \quad (6)$$

2) *Knee Prosthesis Kinematics Analysis*: The kinematics of femoral prosthesis components was analyzed first, which start at the major plane Fi1-plane. This plane is the most important among others because during the intra-operative procedure, this plane is cut first and marked as reference for the next plane. The procedure depends on the experience of surgeon to perform this step by insert intramedullary rod guidance into the femoral canal of the patient's femur, where respect to the anatomical landmarks of the knee. Fig. 6 shows the alignment of distal femoral cutting instrument. At the guidance's head end is attached with first plane cutting block as having a slot to guide the cutting saw. Generally, the conventional procedure performs each step of TKR surgery without accuracy feedback checking. Therefore, the cutting of first plane is the critical step to indicate the finished quality of TKR surgery. Fig. 7 shows the relationship between each plane of knee prosthesis.

The prosthesis planes have features as the geometry shape, which can be determined the relationship between planes by using kinematics analysis. The study of forward kinematics is the static geometrical was applied to compute position and orientation of each plane. In the same way of knee analysis, five Cartesian coordinate system were assigned to each plane as the plane's reference frame, and two major frames were assigned as the femoral prosthesis reference at the center of curvature.

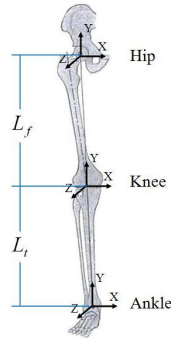


Fig. 5 Frame assignment on mechanical axis alignment of leg

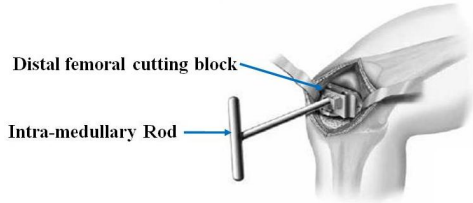


Fig. 6 Alignment of distal femoral cutting instruments

Begin at plane 1 is represented the characteristic by F_{i1} -frame, the origin of frame indicated the position and the direction of three unit vector describe the orientation of the frame. F_{i1} -frame was fixed as base reference or others plane. Then, the description of plane 2 (F_{i2} -frame) was respect to plane 1 by translate along Y and Z -axis with vector ${}^1_2\bar{p}$ and rotate about X -axis with angle θ_2 , the homogeneous transform of plane 2 respect to plane 1 is

$${}_{F_{i2}}^{F_{i1}}H = \begin{bmatrix} R_x(\theta_2) & \vdots \\ \hline 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

Where vector ${}^1_2\bar{p}$ is the displacement from plane 1 to plane 2 in Y and Z -axis can be computed by apply sine and cosine rules.

$${}^1_2\bar{p} = \begin{bmatrix} x_1 \\ y_1 + l_2 / 2 * \sin(\theta_2) \\ z_1 - l_1 / 2 - l_2 / 2 * \cos(\theta_2) \end{bmatrix} \quad (8)$$

The remaining planes can be described as like as plane 2, which respect to plane 1. So, the femoral prosthesis will have four homogeneous transform matrix to describe each plane as ${}_{F_{i2}}^{F_{i1}}H$, ${}_{F_{i3}}^{F_{i1}}H$, ${}_{F_{i4}}^{F_{i1}}H$, ${}_{F_{i5}}^{F_{i1}}H$ and ${}_{F_{i5}}^{F_{i1}}H$

The others two major frames were assigned as the femoral prosthesis frame and match frame to the center of knee. The femoral prosthesis frame can be defined as the center of Both frames were placed in the same orientation as plane 1, for the position define as translate up and down along Y -axis. The curvature of the prosthesis as shown in the Fig. 3 The other one is the frame to match with the center of knee frame.

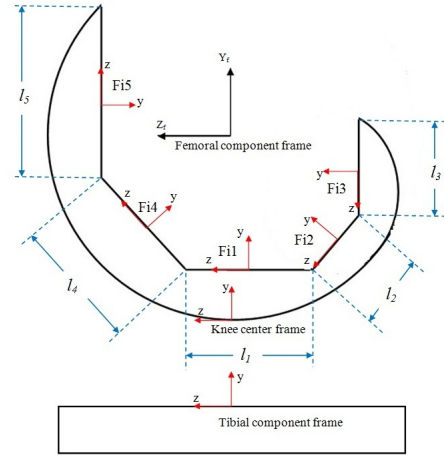


Fig. 7 Shows the relationship between each plane of knee prosthesis.

On the tibia bone, cutting surface is the single flat plane, which should relate to the femoral cutting plane. A Cartesian coordinate system was assigned to the tibial component as the cutting plane reference, which the origin placed on the center point of the prosthesis and the orientation should parallel with plane 1 on the femoral component.

All information of the feature of prosthesis will be retrieved from the data acquisition process by using laser scanner. Therefore all parameters of our model can be modified the value depends on the shape of prosthesis.

C. Kinematics Simulation

The kinematics analysis of implanted knee and prosthesis components was found in the previous section, which can be described the relationship between each body by homogeneous transform. The two modules of kinematics equations are 1) mechanical alignment module, and 2) kinematics of prosthesis module were combined to simulate the leg alignment and motion after TKR surgery. Ideally, this simulation system is the part of TKR navigation system, which should show the virtual graphic of leg and prosthesis to guide the surgeon when insert the intramedullary rod. So, surgeon can be able to adjust and find the proper position and orientation of the insertion.

This study is the first phase to analyze the kinematics and model the equations of leg and prosthesis, which will display the normal mechanical axis alignment compare to 3 pattern of implanted dislocation. 1) location error about Y -axis 10 degrees, 2) location error about Z -axis 10 degrees, and 3) location error about Y -axis and Z -axis 10 degree each.

The model of normal alignment was assigned as reference, then prosthesis models will placed into the knee frame with each error pattern and show the result of mechanical alignment when fully extended knee and tibia flexion in every 10 degree up to 130 degree. The center point of knee flexion was located at the center of femoral component frame, which the model constructed cylinders for the lateral and medial femoral condyle [11].

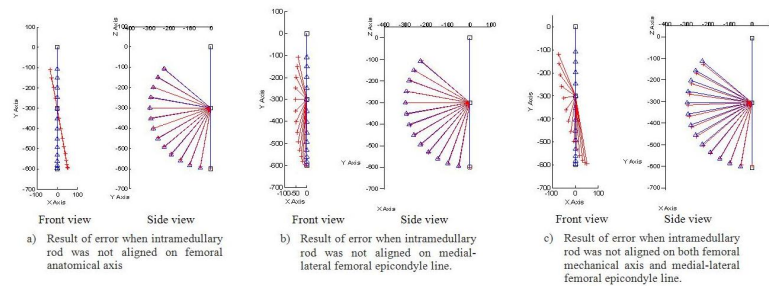


Fig. 8 display the normal mechanical alignment compare to 3 pattern of implanted dislocation

IV. RESULTS

Three cases of simulation display their post-operative result error in the mechanical axis alignment. There are 1) error in orientation about Z-axis, the intramedullary rod was not aligned on femoral anatomical axis, 2) error in orientation about Y-axis, the intramedullary rod's head was not aligned on the medial-lateral femoral epicondyle line, 3) combination error in orientation about both intramedullary orientation using Euler angle. The results were shown in front view and sagittal view to display the mechanical axis angle error and path motion of tibia bone, while being stand full extension and then flexion 10 degree for each step up to 130 degree.

The simulation in case 1 shows that at full extension the angle of hip-knee-ankle was show the abnormal mechanical axis alignment in varus/valgus character and change as a linear while being flexion. Fig. 8 a) shows the result of error when intramedullary rod was not aligned on femoral anatomical axis.

The simulation in case 2 shows that at full extension the angle of hip-knee-ankle was show the normal mechanical axis alignment in front view, and change as a circular while being flexion. Fig. 8 b) shows the result of error when intramedullary rod was not aligned on femoral epicondyle line.

The simulation in case 3 shows that at full extension the angle of hip-knee-ankle was show the abnormal alignment in varus/valgus character, and change as a circular while being flexion. Fig. 8 c) shows the result of error when intramedullary rod was not aligned on both femoral anatomical axis and femoral epicondyle line.

V. CONCLUSION

A 3-Dimensional kinematics model for simulating and displaying post-operative results were developed. The kinematics model was based on hip-knee-ankle alignment, intramedullary rod's axis and anatomical landmarks. Three error cases in total knee replacement surgical practices were explored: (1) TKR error in orientation about intramedullary canal's axis, (2) TKR error in orientation about patella's axis, and (3) TKR with combination errors in case 1 and 2 using Euler angle. The results can display mis-aligned lower-limb system after poor TKR surgical practice. The effect of mis-

alignment would cause a long-term problem for body's postural activities.

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