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Development of an Imageless Navigation System for Total Knee Arthroplasty

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Abstract-**Will being an important part of modern operation room, in recent years computer-aided technology has become more and more integrated in different surgical procedures, such as brain, spine, ENT, hip, knee etc. A vast number of papers have been published on computer assisted knee surgery recently with inspiring clinical results, such as more precise alignment and more minimally invasive. An innovative and universal image-free computer-aided TKA system is introduced in this article. Through dynamic, detailed navigation screens, instruments are accurately depicted in relation to a patient's anatomy to aid femoral and tibial osteotomy, so intramedullary hole drilling and ankle clamp attaching have been avoided. Undermentioned functions are also realized: base kinematics, postoperative kinematics, soft tissue balancing.**

Key words: **computer-aided knee surgery, total knee arthroplasty**

I. Introduction

Several approaches have been used to improve clinical outcomes in total knee arthroplasty (TKA). The first of these is the mechanical approach. Over the last decade, many improvements have been made in the design of mechanical alignment systems, but misalignments are still frequently reported in the literatures with both intra- and extramedullary devices[1][2]. Even with a good prosthesis alignment, the management of the soft tissue is still an important factor in obtaining a good kinematics result with a nonrestricted range of motion and a painless knee.

To address this issue, computer-assisted instrumentation has been developed. A large number of articles have been published on navigated knee surgery using different systems [3]–[7]. So far there have been four categories of CAS systems commercially available in TKA procedure [3], the taxonomy is proposed in Fig. 1.

It is important to distinguish between these systems: (1) Fluoro-based systems using fluoroscopic images to navigate; (2) image-less systems using Bone Morphing; (3) image-less systems using landmarks; (4) CT-based systems.

In this paper we present an image-less navigation system without any pre- or intraoperative images (i.e., no CT, MR, or fluoroscopy). The method depends mainly on landmarks collected with a 3D optical localizer in relative coordinate systems attached to the femur and tibia (Fig.2.). It belongs to category (3).

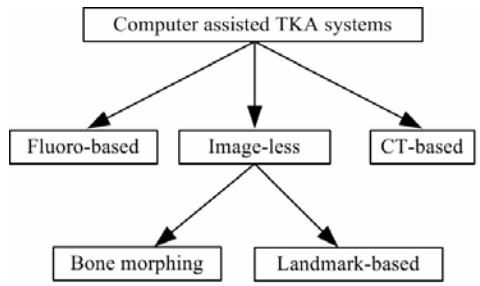

Fig. 1. Taxonomy of computer-assisted TKA systems.

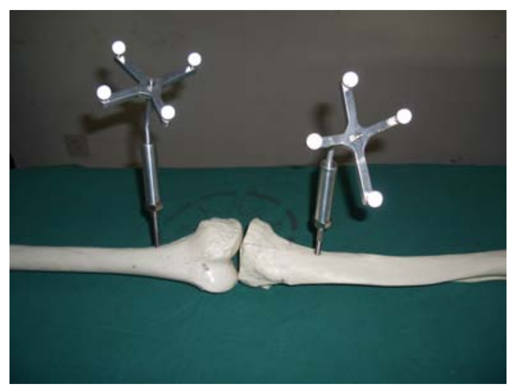

Fig.2. Femur and tibia reference frames

II. Methods

A. Overview

The system we developed is based on the following components: (1) a Polaris (Northern Digital Inc., Waterloo, Canada) optical tracking system; (2) a Dell Windows workstation; (3) femur and tibia reference frames (Fig.2), an oscillating saw probe for adjusting the position of cutting block (Fig.3).

Fig. 4 shows the framework of the system.

B. Procedure

Fig.5 shows the surgery procedure, which mainly consists of attaching reference frames, digitizing landmarks, recording pre- and postoperative kinematics, navigating cuts, balancing soft tissue.

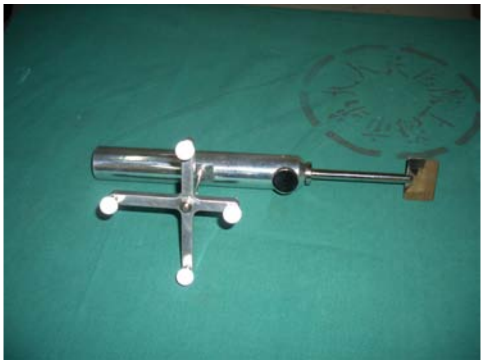

Fig. 3. Oscillating saw probe

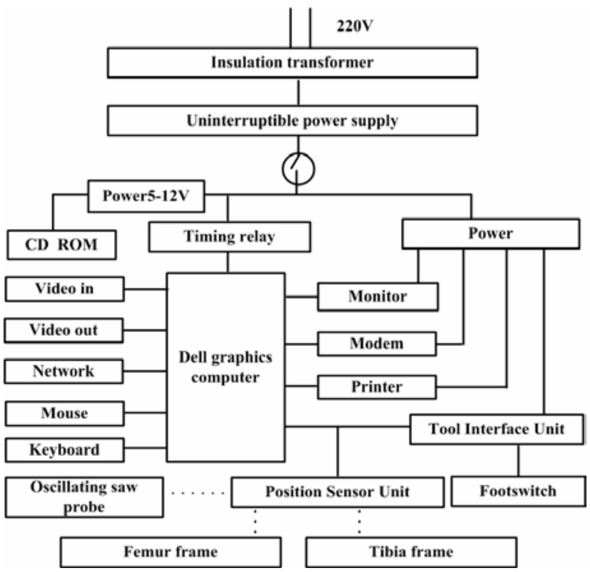

Fig. 4 Framework of the system

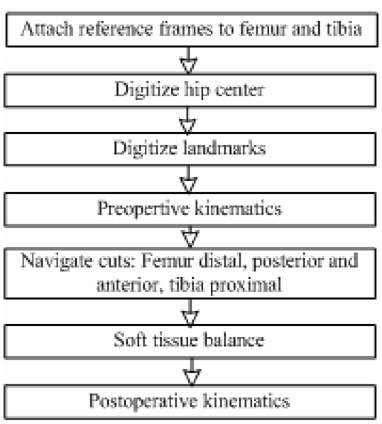

Fig. 5. Surgery Procedure

C. Digitize Hip Center

After attaching femur and tibia reference frames, the location of hip center is required to determine the mechanical femoral axis. It is a very important procedure as it will affect the accuracy of prosthesis alignment. During TKA procedure, the hip is outside the operating field, so detection of hip center is based on a kinematics method. When the surgeon moves the femur in circular in full extension, the subsequent positions of the femoral reference frame are tracked. The hip center is calculated with the least square method, (1) and (2) is used to get this point:

$$f(x,y,z,r)=\sum_{i=1}^{n}(\sqrt{(x_i-x_o)^2+(y_i-y_o)^2+(z_i-z_o)^2}-r)^2 \quad (1)$$

$$\frac{\partial f}{\partial x_0}=\frac{\partial f}{\partial y_0}=\frac{\partial f}{\partial z}=\frac{\partial f}{\partial r}=0 \quad (2)$$

r — radius from femur frame to hip center
x_i, y_i, z_i — location of femur frame
x_0, y_0, z_0 — location of hip center

Reducing pelvic motion can significantly increase the success rate for localizing hip center. So move femur through as large a range of motion as possible, while exerting as little force as necessary on the hip to minimize hip center movement.

D. Digitize landmarks

In order to compute femoral and tibial reference axes for navigation, a set of specific points (Table I) must be identified and saved with the point picking tool.

E. Kinematics

After digitizing landmarks on the femur, tibia, and ankle to compute the anatomic reference axes, our system allows the surgeon to gain baseline knowledge about the range of motion of the leg before the actual procedure is performed. This data can be used for comparison purposes after the procedure is completed. Real time measurements for varus/valgus, flexion/extension, internal/external rotation, and AP drawer are displayed（TableⅡ）. The maximum flexion ranges for each motion category are also displayed and saved (TableⅢ).

TABLE I

ANATAMY LANDMARKS

Femur	Tibia	Ankle
Post. Lat. Condyle	Medial Defect Point	Medial Malleolus
Post. Med. Condyle	Lateral Defect Point	Lateral Malleolus
Lat. Epicondyle	Tibial Center	
Med. Epicondyle	Tuberosity	
Anterior Cortex		
Dist Lat. Condyle		
Dist. Med. Condyle		
Femur Center		

TABLE II

MAXIMUM RANGE OF PRE AND POST KINEMATICS

	Preoperative	Postoperative
Varus/Valgus	8º/6º	12º/ 9º
Int./Ext. Rot	25°/35°	29°/40°
Flexion/Extension	0°/120°	5°/140°
AP translation	4mm	2mm

TABLE III

MAXIMUM FLEXION RANGE OF EACH MOTION

	Preoperative	Postoperative
Varus/Valgus	5º-120º	3º-140º
Int./Ext. Rot	4º-20º	0º-30º
AP translation	30º-65º	45º-55º

F. *Navigate Cuts*

We use an oscillate saw probe to complete the setting of the cutting guides for tibia and femur. During navigation, plane of the probe is tracked to align the cutting plane.

Fig.6 shows navigating femur distal cut.

Fig.7 shows navigating femur posterior cut.

Fig.8 shows navigating femur anterior cut.

Fig.9 shows navigating tibia proximal cut.

G. *Soft Tissue Balancing*

There are two key points in obtaining good clinical outcome for TKA: (1) the alignment of the prosthesis with respect to the mechanical axis, and (2) the balance of soft tissue.

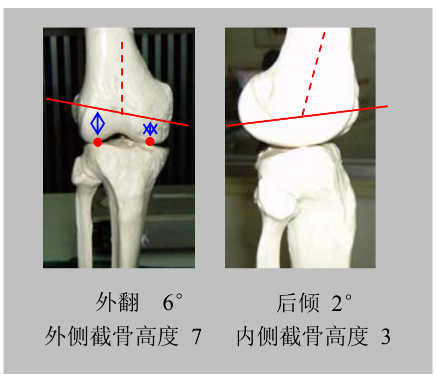

Fig.6. Navigate femur distal cut

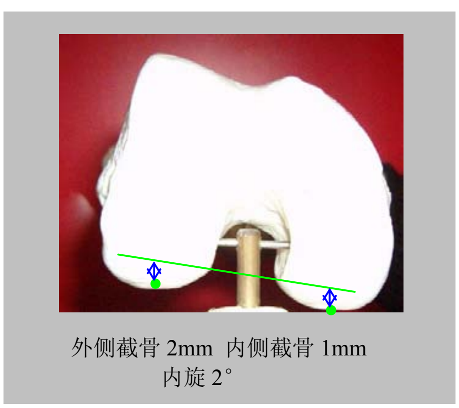

Fig.7. Navigate femur posterior cut

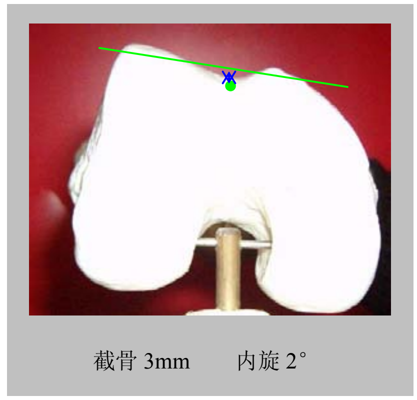

Fig.8. Navigate femur anterior cut

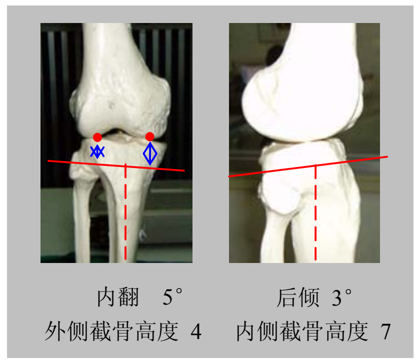

Fig.9. Navigate tibia cut

The soft tissue balancing is done by using the measurements of distance between the tibia and femur cutting plane over the entire range of knee flexion to help ensure the knee is balanced throughout.

This procedure is performed after the bone cuts have been made and a spacer block is placed in the knee gap. The user selects the knee flexion angle at which to perform the test, then applies varus/valgus loads to the knee. The system records maximum medial and lateral distractions in a table, then test next angle. Distraction value groups are only calculated and displayed when the flexion is at the required, predefined test angle. During testing, the current flexion and varus/valgus in real time are also displayed.

Fig.10 shows the result of a corpse bone experiment.

III. RESULTS

Intra-operative surgical navigation can eliminate the use of intra- and extramedullary alignment guides while improving alignment accuracy of TKA, so navigation of TKA has the potential to improve both short and long-term outcomes and decrease morbidity following conventional procedure. Common problems that can be improved or eliminated by surgical navigation include:

- Improper alignment of the femur or tibia.
- Malrotation of the components which can lead to excessive wear and patellar maltracking.

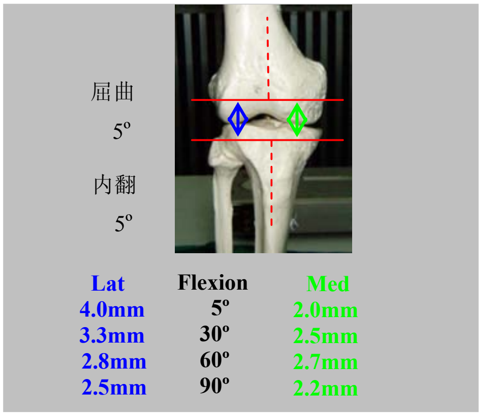

Fig.10. Navigate soft tissue balance

- Improper ligament balancing in flexion and extension.
- Bone marrow and fat embolism syndrome.

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