Acta Biomed 2017; Vol. 88, Supplement 2: 32-37 DOI: 10.23750/abm.v88i2 -S.6509

Original article

Total knee replacement: intraoperative and postoperative kinematic assessment

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Summary. *Background and aim:* The main goals of the total knee arthroplasty (TKA) is to reduce the perceived pain and restore knee mobility and function in case of osteoarthritic knees joints. Literature shows how the three major causes of TKA failures are related to wear, loosening and instability and this is due to a problem of imbalance and malalignment. Intraoperative and postoperative kinematics analysis could be of benefit for improving surgery outcome. The aim of the present paper is to give an overview of the two set-up with the highest accuracy for intraoperative and postoperative TKA kinematics evaluation, currently in use at Istituto Ortopedico Rizzoli. *Introperative and Postoperative Evaluation:* For intraoperative evaluation it has been presented a navigation system with a specifically developed software, while for the postoperative it has been presented the roentgen stereophotogrammetric analysis (RSA). The navigation system consists in a laptop connected with an optoelectronic localizer (Polaris, Northern Digital Inc, Canada). Two reference arrays with passive optical markers and a marked probe are used to localize the knee joint in the 3D space and track the joint kinematics. The RSA is a radiographic technique used in orthopaedic field for measuring micromotion at bone/prosthesis interface or for joint kinematics evaluation. The RSA uses two X-ray sources synchronized with two digital flat-panels. *Conclusions:* The present paper shows that using the navigation system allows the surgeon to easily perform kinematic and alignment evaluation during TKA surgery while the RSA allows a quantitative evaluation of the joint kinematics during the recovery time. (www.actabiomedica.it)

Key words: knee, arthroplasty, kinematic

Introduction

The main goals of the total knee arthroplasty (TKA) is to reduce the perceived pain and to restore knee mobility and function for the treatment of osteoarthritic knees joints. Unfortunately, different biomechanical studies have shown an abnormal tibial rotation and anterior tibial translation after TKA surgery (1-5).

Scientific literature has underlined how an alteration of the knee motion pattern could lead to an abnormal wear in knee prosthesis components as well as an alteration in joint knee soft tissue (6)(7-9). Moreover, between 72% and 86% of the patients after TKA report to be satisfied with their postoperative condition (10-11). Unfortunately, such improvement may not be confirmed over long time of follow up. Nearly 10% of the cases require a revision surgery within 10 years of the TKA surgery because of implant loosening (12). Scientific literature reports how the three major causes of failures are related to wear, loosening and instability and this is due to a problem of imbalance and malalignment, both related to surgical technique. In particular, with only three degrees of deviation from the ideal limb alignment along the coronal plane, the risk of surgery failure significantly increases (13). As an example, the malpositioning of the femoral component is a critical aspect in knee joint replacement. Therefore, different intraoperative strategies, based on both kinematics and anatomical evaluation have been developed and used in computer assisted surgery to optimize the implant positioning. Today, navigation system is considered the gold standard for intraoperative kinematics and implant positioning evaluation. In fact, it allows a concrete solution for quantifying and improving accuracy in implant positioning and kinematics outcome.

Nowadays, the navigation system for intraoperative evaluation has various applications. In particular, it can be used for the planning of the surgery (using also radiological images software), for optimization of the cutting procedures, for intraoperative evaluation of joint kinematics or for in-vivo biomechanical assessment. Moreover, in case of revision surgery, the use of the navigation assistance allows the surgeon to control the joint line, even when the bone is missing giving a great aid for the correct implantation.

Anyway, the prosthetic implant evaluation does not end with the intraoperative assessment.

In fact, a non-invasive, precise and reliable method able to measure joint kinematics might provide clinically relevant information about the functional behavior of the joint, starting from the injury event until to the rehabilitation phase. For this reason, the interest in quantitative analysis of the knee joint kinematics, even with non-invasive devices, has increased during the last years allowing also a quantitative and comparable postoperative evaluation.

The aim of the present manuscript is to give an overview of the two set-up with the highest accuracy for intraoperative and postoperative TKA evaluation, currently in use at Istituto Ortopedico Rizzoli. Those techniques are the navigation system with a specifically developed software and the roentgen stereophotogrammetric analysis.

Intraoperative evaluation

Intraoperative passive kinematics can be measured with an intraoperative navigation system (BLU-IGS, Orthokey LLC, USA) provided with a specific software for TKA surgery (KLEE, Orthokey LLC, Lewes, Delaware, USA) (14-16). In particular, the navigation system consists in a laptop connected with an optoelectronic localizer (Polaris, Northern Digital Inc, Canada) (Figure 1). Its use neither altered the original surgical technique nor affected knee joint kinematics. The software has been designed to allow flexible anatomical and kinematics acquisitions. The navigation system also needs two reference arrays with passive optical markers and a marked probe. After exposing the knee, the surgeon needs to attach the reference frames to the distal femur and to the proximal area of the tibia. The navigation system protocol consists of two different and essential phases. The first one consists in the anatomical registration.

In particular, to define the anatomical systems of reference, it is required to locate the hip joint center by a femoral circumduction movement and to define the standard anatomical landmarks using the marked probe. Moreover, it is required to acquire the coordinates of the medial and lateral epycondyle, the medial and lateral malleolus and the most medial and the most lateral point of the tibial plateau. The second phase is the kinematic evaluation of knee joint laxity that is repeated both before and after the prosthetic implant.

In fact, after the definition of the anatomical systems of reference it is possible to acquire passive kinematics tests. In particular, it is possible to test the knee joint during varus-valgus (VV) rotation at 0° and at 30° of flexion, internal-external (IE) rotation at 30° and 90° of knee flexion and the anterior-posterior (AP) translations at 30° and 90° of knee flexion. Also the passive range of motion from maximum extension to maximum knee flexion can be evaluated. During both the first and the second phase the software interface guides the surgeon through the acquisition steps and shows the results in real-time. Specifically, the software interface contains the field of view of the trackers, the command

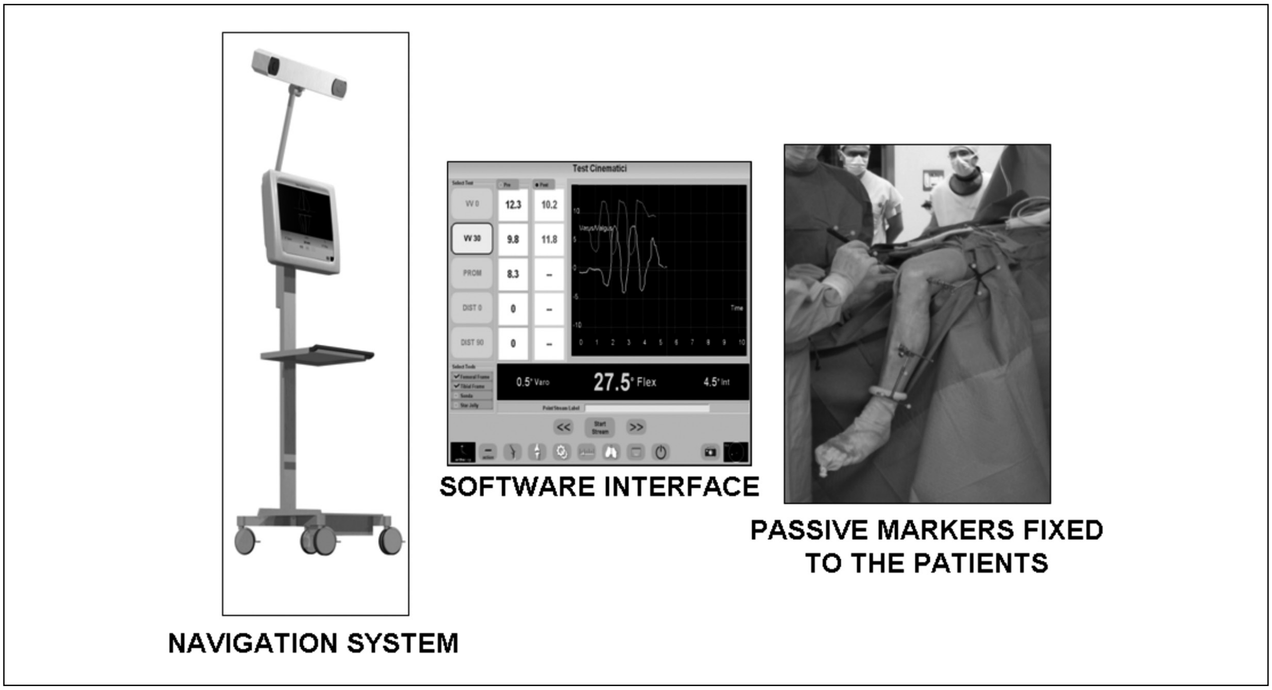

Figure 1. Navigation system and its software interface. Passive markers fixed to the patient for intraoperative evaluation during anatomical registration phase

buttons and an area where the results of the acquisition are graphically shown.

The scientific literature offers an evaluation of test-retest repeatability for the used navigation system that is equal to 0.97 when performed by the same surgeon and 0.87 when performed by different surgeons. While the intra-tester repeatability was reported to be about 1 mm for translational and 1° for rotational assessment (15, 17). Moreover, the system was reported by the producer to have a 3D RMS volumetric accuracy of 0.350 mm and a 3D RMS volumetric repeatability of 0.200 mm.

Instantaneous rotations and translations are usually computed from the relative motion of the tibial frame with respect to the femoral frame using the Grood and Suntay algorithm (18). All the kinematics test are performed at the manual-maximum load value by the surgeon. The surgical reconstruction is then performed by following the standard indications for the implanted prostheses. The navigation software is also able to evaluate the alignment of the prosthetic implant. After the implantation of the prosthesis the knee kinematics is evaluated from data acquired during laxity tests and passive motion, by comparing data obtained before and after the implantation.

Postoperative evaluation

The importance to monitor the knee joint kinematics even after the TKA surgery led to the development of non-invasive techniques that make possible to monitor the joint function especially during the recovery time.

One of the most popular non-invasive technique is represented by the fluoroscopy. Fluoroscopy is used to track the kinematics of a 3D models that can be realized using both the tibial and the femoral CT examinations of the patient or the tibial and femoral components of a total knee prosthesis extracted from a CAD files. The 3D model is then matched to the two-dimensional features of the acquired fluoroscopic images (19-21).

The development of these procedures, have also assessed bone motion during functional activities, such as weight-bearing flexion, single-legged hop and jump cut maneuvers. The main problem with such technique is the occurrence of errors in out-of-plane translations and rotations, which affects the applicability of the method for measuring the 3D components of a movement (22-24).

According to the literature Li et al. (25) were the first to perform in-vivo studies of joint kinematics matching MRI-based bone models or prosthetic CAD models to biplane fluoroscopic images using a series of static fluoroscopic acquisitions. Subsequently, this technique was further developed to measure dynamic knee joint motion (26, 27).

A further developed non-invasive technique is the roentgen stereophotogrammetric analysis (RSA), that is a technique based on the principles of optical photogrammetry.

The RSA is a radiographic technique, developed in 1974, with high accuracy used in orthopaedic field for measuring micromotion at bone/prosthesis interface or for joint kinematics evaluation.

In fact, the RSA is the most accurate technique for the measurement of micromotion between rigid bodies in 3D space (estimate precision of 0.2 mm for translational displacement and 0.3° for rotations) (28, 29) making it one of the gold standard for biomechanical assessment of the skeletal system.

Today there are different types of RSA techniques (i.e. static, dynamic, marker or bone based) that offer different advantages and applications. According to this, different evaluations can be performed such as the stabilization and the sinking of prosthetic implants, the stability of the fractures, the kinematics of the different joints as well as the function of the ligaments (evolution of knee laxity). The dynamic RSA setup for in-vivo knee kinematics analysis uses a clinical biplane fluoroscopic image system.

For the RSA analysis, two X-ray sources are synchronized with two digital flat-panels with a field of a view of 43x43 cm (Figure 2). The frame rate is 8 frames-per-seconds (fps). The two tubes allow the simultaneous emission of X-rays to obtain a three-dimensional reconstruction of the segments to be analyzed defined by the acquisition of two radiographic images. The generators are positioned ortogonally to each other and controlled by the same control button.

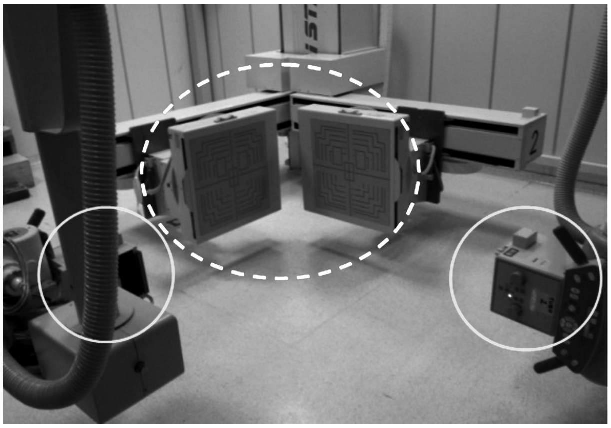

Figure 2. X-ray sources (solid line) synchronized and digital flat-panels (dashed line) for RSA.

The kinematical parameters are evaluated using the Grood and Suntay decomposition (18) and the Low-point kinematics. The reference systems are associated to the femoral and tibial bone.

The motor tasks that are usually performed are: sit to stand (from the sitting position, the patient stands up), range of motion (the patient is asked to extend the knee from the maximum flexion to the maximal extension movement), descent with impact (descent from a single step with the operated limb the impact the floor as first), controlled descent (descent from a single step with the controlateral limb the impact the floor as first), level walking (the task was a simple step performed starting with the operated limb).

A custom software for RSA data elaboration has been developed at Istituto Ortopedico Rizzoli using MATLAB (Matlab, MathWorks, USA). Using this specific software, it has been possible to delevop a data processing protocol that comprises the following steps: 1) distortion correction for sequence images; 2) calibration of the biplane system configuration relative to a global reference 3D coordinate system; 3) acquisition of 3D coordinates of bone markers; 4) extraction of kinematic data.

Discussion

The present manuscript shows that navigation system might be used to easily analyse kinematic patterns throughout the range of motion of TKA and to optimize the limb alignment.

In fact, the navigation system is now considered a useful device for in-vivo research, for standardization and for the control of surgical prosthetic implantation especially during the most complicated cases. Improving postoperative kinematics and the possibility of monitoring it over the course of time, together with improvements in design, fixation and biomaterial durability, may be one of the most important solution for increasing patients' satisfaction and function after TKA surgery.

The use of the navigation systems to evaluate knee kinematics provide a quantitative and solid information on knee joint behaviour and data comparable to postoperative evaluation. This means that they could be used as a first time evaluation of prosthetic function during surgery.

Given the underlined importance of keeping monitored the implanted prosthesis and the subsequent kinematics, the present manuscript address the RSA as a feasible methodology for this purpose. It could be also interesting to compare some motor tasks intraoperativelly acquired with the navigation system with those performed postoperatively and acquired with the RSA.

Of curse the nature of the performed tasks is different and needs to be taken under consideration. In fact, in the intra-operative evaluation, the limb is subjected to passive stress while in the postoperative evaluation there is an active movement, with muscular contraction and proprioceptive control. An other crucial point during an RSA acquisition is the ability of the patients to perform the required motor tasks. Especially for what concern the execution of the descents, many patients, belonging to the elderly population feel unstable. For a correct analysis it is necessary to find tasks that allow the detection of instabilities without stressing the patients. Moreover, some future developments will include the dynamic RSA technique in integrated protocols with motion capture system, force plate and systems able to study the proprioceptive control.

In conclusion, the present paper shows that using computer navigation allows the surgeon to easily perform kinematic and alignment evaluation during TKA surgery while the RSA allows a quantitative evaluation of the joint kinematics during the recovery time that is fundamental for monitoring the implant conditions.

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Received: 2 April 2017
Accepted: 3 May 2017
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