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Original article

Influence of the optical system and anatomic points on computer-assisted total knee arthroplasty

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ABSTRACT

Background: For over a decade, computer-assisted orthopaedic surgery for total knee arthroplasty has been accepted as ensuring accurate implant alignment in the coronal plane.
Hypothesis: We hypothesised that lack of accuracy in skeletal landmark identification during the acquisition phase and/or measurement variability of the infrared optical system may limit the validity of the numerical information used to guide the surgical procedure.
Methods: We built a geometric model of a navigation system, with no preoperative image acquisition, to simulate the stages of the acquisition process. Random positions of each optical reflector center and anatomic acquisition point were generated within a sphere of predefined diameter. Based on the virtual geometric model and navigation process, we obtained 30,000 simulations using the Monte Carlo statistical method then computed the variability of the anatomic reference frames used to guide the bone cuts. Rotational variability (α, β, γ) of the femoral and tibial landmarks reflected implant positioning errors in flexion-extension, valgus-varus, and rotation, respectively.
Results: Taking into account the uncertainties pertaining to the 3D infrared optical measurement system and to anatomic point acquisition, the femoral and tibial landmarks exhibited maximal alpha (flexion-extension), beta (valgus-varus), and gamma (axial rotation) errors of 1.65° (0.9°); 1.51° (0,98°), and 2.37° (3.84°), respectively. Variability of the infrared optical measurement system had no significant influence on femoro-tibial alignment angles.
Conclusion: The results of a Monte Carlo simulation indicate a certain level of vulnerability of navigation systems for guiding position in rotation, contrasting with robustness for guiding sagittal and coronal alignments.
Level of evidence: Level IV.

1. Introduction

For over three decades, the correct positioning of total knee arthroplasty (TKA) components has relied on conventional ancillary systems involving intra-medullary or extra-medullary guides. With these systems, bone cut guides are positioned, with a variable degree of accuracy [1–4]. Patient-specific guides may hold promise for the future but have not been proven sufficiently accurate to warrant their use as a reference procedure [5–9]. Computer-assisted orthopaedic surgery was introduced over 10 years ago and has been found to improve implant position accuracy in the coronal plane compared to conventional instrumentation [10–16]. Nevertheless, errors related to the infrared optical detection system and to lack of accuracy in anatomic landmark identification by palpation may escape detection [17,18]. Geometric models characterising TKA navigation systems have been developed to allow numerical simulations that incorporate the various stages of the acquisition process.

We hypothesised that navigation system accuracy was potentially compromised by the variability of the optimal measurement system and of the anatomic points identified by the surgeon during the navigation procedure.

2. Material and methods

2.1. Development of the geometric model

The geometric model of the navigation system (Fig. 1) was patterned after the Praxim Nanostation. It replicates the left skeletal

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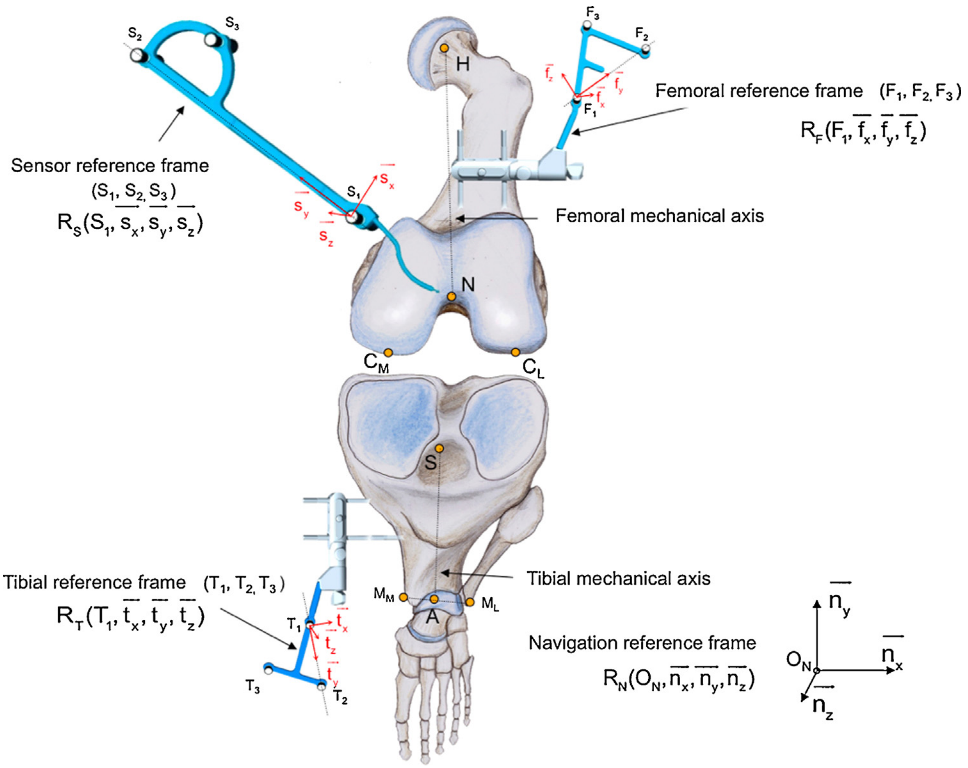

Fig. 1. Frames of references used by the 3D optical measurement system during total knee arthroplasty.

lower limb of a patient installed in the operating room, after surgical exposure of the knee and positioning of the femoral and tibial frames of reference. Tables 1a and 1b list the variables and anatomical measures used. The femoral ('F' shape) and tibial ('T' shape) rigid bodies were assumed to be each secured to the skeleton by two Hoffman-type bicortical external fixators, each equipped with an orientable connector allowing the rigid body to be positioned then fixed in front of the camera.

2.2. Construction of the skeletal frames of reference

Each frame of reference comprised three reflective optical trackers attached to a titanium rigid body. The landmarks related to each frame of reference were determined based on three separate geometric points, located at the centres of the three reflective optical trackers on each rigid body (Fig. 2). For example, the R_T frame of reference associated with the tibia was composed of three orthogonal unit vectors, $\vec{t}_x$, $\vec{t}_y$, and $\vec{t}_z$, whose origin was point T_1.

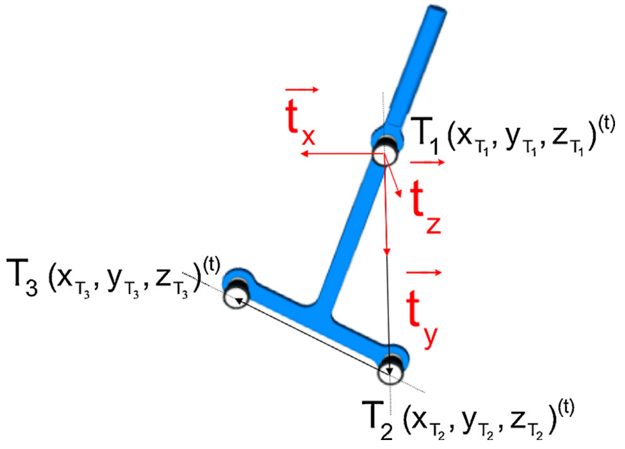

Fig. 2. Construction of the tibial frame of reference.

At each instant, the coordinates of $\vec{t}_x$, $\vec{t}_y$ and $\vec{t}_z$ were expressed in the navigator frame of reference R_N and derived from the coordinates of points T_1 (X_{T1}, Y_{T1}, Z_{T1}), T_2 (X_{T2}, Y_{T2}, Z_{T2}), and T_3 (X_{T3}, Y_{T3}, Z_{T3}), according to the following equations:

$$\vec{t}^{\,(t)}_{y\,/\bar{R}_N} = \frac{\overrightarrow{T_1T_2}}{\left\|\overrightarrow{T_1T_2}\right\|},\ \vec{t}^{\,(t)}_{z\,/R_N} = \frac{\overrightarrow{T_1T_2}\wedge\overrightarrow{T_1T_3}}{\left\|\overrightarrow{T_1T_2}\wedge\overrightarrow{T_1T_3}\right\|},\ \vec{t}^{\,(t)}_{x\,/R_N} = \vec{t}^{\,(t)}_{y\,/R_N}\wedge\vec{t}^{\,(t)}_{z\,/R_N}$$

where ^{t} is the time at computation.

We used the same method for real-time definition of the frames of reference $R_F\left(F_1, \vec{f}_x, \vec{f}_y, \vec{f}_z\right)$, and $R_S\left(S_1, \vec{s}_x, \vec{s}_y, \vec{s}_z\right)$ associated with the femur and mechanical acquisition sensor, respectively, using the centres of the reflective optical trackers (F_1, F_2, F_3) and (S_1, S_2, S_3).

2.3. Modelling of the acquisition phase of the anatomic points

The sequence of acquisition procedures used the three main steps) to compute the coordinates of an acquisition point M_i as a function of time in each frame of reference. To compute the coordinates of an acquisition point M_i as a function of time in each frame of reference, the acquisition sequence goes through a three-step procedure. The detailed equations are shown in the online-only appendix.

The second step allowed instantaneous computation of the coordinates of the same acquisition point within the femoral reference frame. The coordinates of M_i within this local reference frame did not vary with femur position or degree of knee flexion.

The third step consisted in determining the new coordinates of the anatomic point M_i after each manipulation of the lower limb.

2.4. Construction of the anatomical points

The femoral and tibial anatomic points were determined based on the instantaneous positions of all the M_i anatomic points (Fig. 3).