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ORIGINAL ARTICLE

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Navigated intraoperative analysis of lower limb alignment

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Abstract *Introduction*: Accurate intraoperative assessment of lower limb alignment is crucial for the treatment of long bone fractures, implantation of knee arthroplasties and correction of deformities. During orthopaedic surgery, exact real time control of the mechanical axis is strongly desirable. The aim of this study was to compare conventional intraoperative analysis of the mechanical axis by the cable method with continuous, 3-dimensional imaging with a navigation system. *Materials and methods*: Twenty legs of fresh human cadaver were randomly assigned to conventional analysis with the cable method ($n=10$) or navigated analysis with a fluoroscopy based navigation system ($n=10$). The intersection of the mechanical axis with the tibia plateau was presented as percentage of the tibia plateau (beginning with 0% at the medial border and ending with 100% laterally). CT-scans were performed for all legs and the CT-values of the mechanical axis were compared to the measurements after cable method and navigation. Furthermore, the radiation time and dose area product of both groups for single analysis of the mechanical axis was compared. *Results*: Conventional evaluation of the mechanical axis by the cable method showed $6.0 \pm 3.1\%$ difference compared to the analysis by CT. In the navigated group the difference was $2.6 \pm 1.8\%$ ($P=0.008$). Radiation time and dose area product were highly significantly lower after conventional measurement. *Conclusions*: Navigated intraoperative evaluation of the mechanical axis offers increased accuracy compared to conventional intraoperative analysis. Furthermore, navigation provides continuous control not only of the mechanical axis, but also of the sagittal and transverse plane. Using the cable method, radiation exposure depends on the number of measurements and is lower compared to the navigation system for single intraoperative analysis of the mechanical axis, but may be higher in case of repeated intraoperative measurements.

Keywords Navigation · Mechanical axis · Imaging Accuracy · Deformities · Fractures · Arthroplasties

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Introduction

Malalignment is a significant cause of early degenerative changes and dysfunction [20]. Already small alterations of the mechanical axis cause changes of the load distribution of the knee joint and thus influence the development of osteoarthritis [5, 18]. Under- or overcorrection is a significant cause for failed high tibia osteotomies [4, 13, 17, 23]. In the treatment of lower limb fractures, degenerative changes can follow even small malalignment [9, 27]. Correct alignment is also a substantial factor affecting the long-term results of total knee arthroplasty [2, 6, 11].

Modern methods of fracture fixation, total knee arthroplasty and corrective osteotomies allow absolute control and fine adjustment of bone alignment. Most often malalignment is due to insufficient intraoperative visualisation of the anatomical or mechanical axis. In the operating room long radiographs are not technically possible. There is no absolutely satisfying method to determine the mechanical axis intraoperatively. Krettek et al. [10] introduced the "cable method" using a diathermy cable spanned between the hip and ankle centre, and assessed the mechanical axis by the projection of the diathermy cable at the knee joint. This method is easy to apply intraoperatively and is not associated with special costs. Saleh et al. [19] introduced a technique using a grid with lead-impregnated reference lines. The gird is placed in a sterile bag under the limb and the reference lines of the grid are aligned with the mechanical axis. Paley [15] recommends measuring the joint orientation angles on conventional intraoperative radiographs for corrective osteotomies. All these intraoperative techniques are helpful, but provide only momentary evaluation and can be associated with several technical mistakes [10, 15, 19]. Therefore, accurate and continuous intraoperative visualisation of the mechanical axis is strongly desirable. To the best of our knowledge, no publication has compared conventional imaging of the mechanical axis with the cable method and evaluation of the mechanical axis under navigational guidance.

Materials and methods

Twenty legs of fresh human cadavers were randomly assigned to conventional analysis of the mechanical axis with the cable method ($n = 10$) or analysis with a navigation system ($n = 10$). The mechanical axis was defined by a line from the centre of the femoral head to the centre of the ankle [3, 16]. In order to simplify intraoperative measurement of the mechanical axis, the intersection on the mechanical axis with the tibia plateau was presented as percentage of the tibia plateau, which was divided from 0% (medial border) to 100% (lateral border).

In the conventional group the intraoperative mechanical axis was evaluated by the cable method: the knee was fully extended and the patella faced anterior. With the image intensifier beam strictly vertical, the centre of the femoral head (Fig. 1a) and the centre of the ankle were marked (Fig. 1b). A diathermy cable was spanned between these two points and the image intensifier centred on the knee joint. The mechanical axis was determined using the projection of the cable on the image intensifier (Fig. 1c–e) [10].

For navigated evaluation of the mechanical axis, a fluoroscopy based navigation system was used (HTO, Medivision, Oberdorf, Switzerland). This navigation module was originally developed for high tibial osteotomies. Dynamic reference bases were attached to the femur, proximal and distal tibia with a pair of 4.0 mm half pins (Fig. 2a), in order to track the motion of the corresponding bones or fragments when the leg is moving. The anatomical landmarks of the hip, knee and ankle joint were registered under fluoroscopic control: the centre of the hip joint was registered on ap and lateral images with the help of concentric circles. The tibial plateau was registered with bi-plane fluoroscopic reconstruction using knee ap and lateral images and the most lateral, medial, anterior, and posterior point at the tibial plateau marked [8]. The knee centre was calculated as the centre of the tibial plateau. At the ankle joint, on ap and lateral image the centre was defined as the middle point of the talus between the medial and lateral shoulder by using a digital ruler. The mechanical axis was defined as a line between the centre of the hip joint to the centre of the ankle joint. The dose area product of the image intensifier (Exposcop 8000, Ziehm, Nuernberg, Germany) and the radiation time was noted in both groups.

All legs were investigated by the CT-scans. The scans were repeated if the patella did not face strictly anterior. The intersections of the mechanical axis with the Fujisawa-line of all legs were measured with a special software (MediCAD, Hectec, Altfraunhofen, Germany). The differences between the measurements by conventional analysis and CT-analysis were calculated. In the same way, the differences between navigated measurements and CT-analysis were noted. Furthermore, the average mechanical axes of all measurements in both groups and after CT were calculated. For statistical analysis paired t-test was applied (SPSS 11.5, SPSS Inc., Chicago, USA).

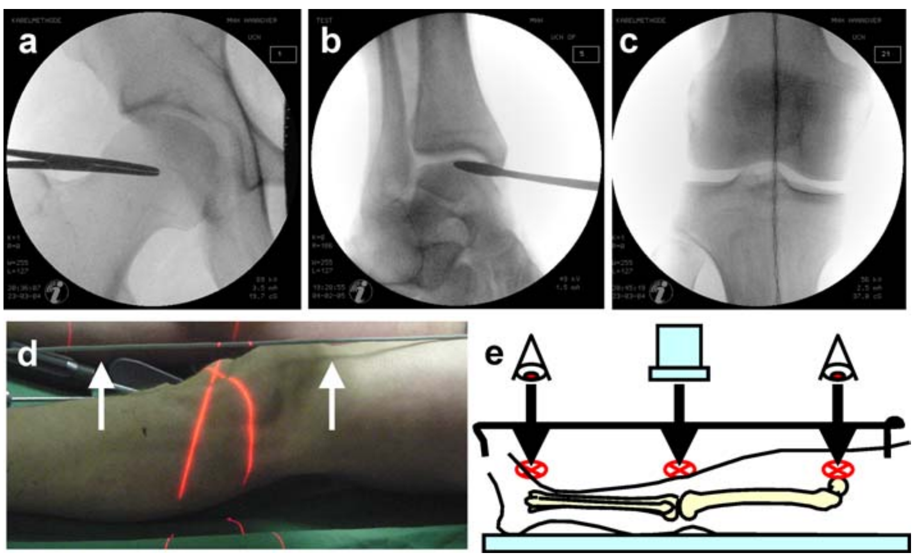

Fig. 1 a–d Intraoperative evaluation of the mechanical axis by the cable method. **a, b** Identification of the hip and ankle centre with the image intensifier. **c–e** The diathermy cable (*white arrows* in **d**,laser cross at the level of the knee to determine the joint centre clinically in d) is spanned between these two points and alignment determined using the projection of the cable

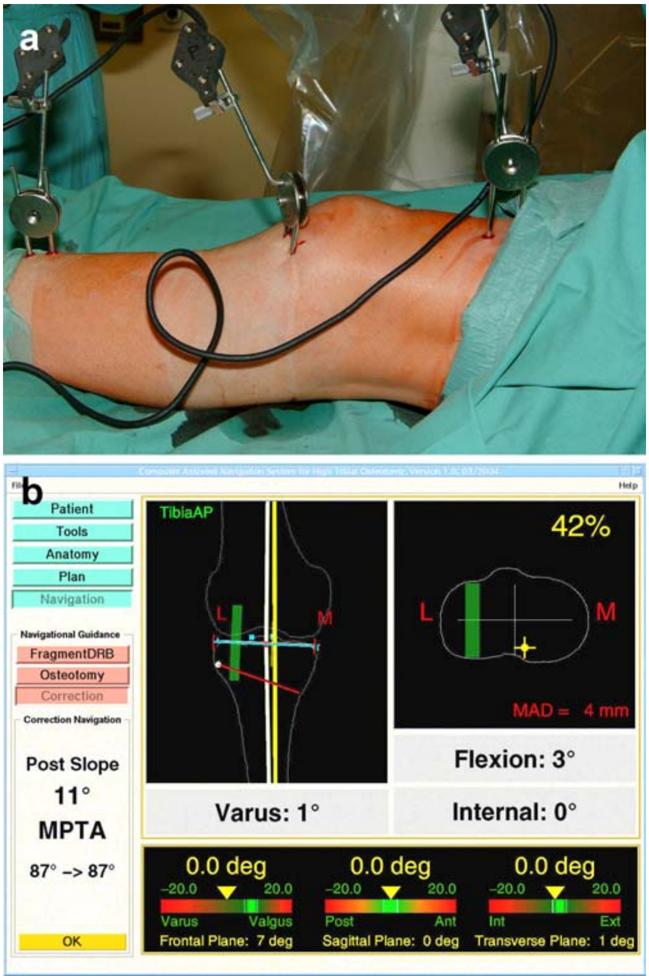

Fig. 2 a, b Evaluation of lower limb alignment with a navigation system. **a** Dynamic reference bases are attached to the femur and tibia, in order to track the motion of the corresponding bones or fragments. **b** After image acquisition of the hip, knee and ankle joint in two planes and registration of the hip, knee and ankle joint centre, the navigation system provides real-time imaging of the axis in the frontal, sagittal and transversal plane

Results

Conventional evaluation of mechanical axis by the cable method showed 6.0 ± 3.1% difference of the intersection at the tibia plateau compared to the CT analysis. In the navigated group the difference to the CT analysis was 2.6 ± 1.8% (P = 0.008). The average intersection of the mechanical axis of all ten measurements by the cable method was at 42.9 ± 7.8% (34.1–54.8%). CT based analysis of these legs revealed an average intersection at 43.4 ± 7.9% (30.9–53.2%). In the navigated group the mechanical axis of all the ten measurements intersected the tibia plateau at 42.1 ± 8.5% (28.6–57.1%) on the average. In the CT-analysis the intersection of these legs was at 42.5 ± 8.4% (30.8–54.7%).

Radiation time after conventional analysis was 11.5 ± 4.0 s (6–18 s), compared to 23.4 ± 7.2 s (16–37 s) after navigation (P < 0.001). The average dose area product after conventional analysis was 9.6 ± 3.3 cGy/cm^2 (5.7–15.6 cGy/cm^2) and differed significantly from navigated analysis (20.9 ± 5.5 cGy/cm^2, 13.1–27.9 cGy/cm^2) (P < 0.001) (Table 1).

Discussion

Exact intraoperative determination of the mechanical axis is a significant clinical problem. Several techniques like the cable method, grids with lead-impregnated reference lines, or assessment of joint orientation angles have been introduced to solve this problem [10, 15, 19]. However, these techniques can be associated with several technical mistakes and provide only momentary assessment. Thus, there is no real satisfying method to determine the intraoperative mechanical axis so far.

The problem of exact intraoperative control of the mechanical axis can be addressed with navigation systems. This study revealed that determination of the mechanical axis with a navigation system is significantly more accurate than the cable method. Five percentage of alteration of the mechanical axis intersection with the tibia plateau roughly correlates to 1° change of the mechanical axis [26]. Thus, the average difference between the conventional mechanical axis analysis compared to the CT based analysis was about 1.2°, whereas the average differences for navigated measurement was about 0.6°. As small alterations of the mechanical axis lead to significant changes of the load distribution of the knee joint, this difference between conventional and navigated analysis may be clinically relevant.

In addition, navigation systems provide intraoperative real time control not only of the frontal, but also of the sagittal and transverse plane. The use of navigation systems seems to be very promising to increase the accuracy of fracture fixation and deformity correction.

Table 1 Determination of the mechanical axis by the cable method and by a navigation system in comparison to CT analysis. Evaluation of the radiation time and dose area product

	Mean absolute value (%, range)	Mean CT value (%, range)	Difference to CT (%)	Radiation time (s, range)	Dose area product (cGy/cm^2, range)
Conventional analysis	42.9 ± 7.8 (34.1–54.8)	43.4 ± 7.9 (30.9–53.2)	6.0 ± 3.1%	11.5 ± 4.0 (6–18)	9.6 ± 3.3 (5.7–15.6)
Navigated analysis	42.1 ± 8.5 (28.6–57.1)	42.5 ± 8.4% (30.8–54.7)	2.6 ± 1.8%	23.4 ± 7.2 (16–37)	20.9 ± 5.5 (13.1–27.9)
P value			0.008	< 0.001	< 0.001

In total knee arthroplasty, some studies have already proven that navigation systems give a better correction of the alignment of the leg and orientation of the components compared to the conventional technique [2, 7].

In our study design, radiation time and dosage were significantly higher in the navigated group for a single analysis of the mechanical axis. However, during surgery analysis of the mechanical axis is usually repeated. In contrast to conventional methods, navigated analysis does not require any additional radiation. Furthermore, additional information by continuous 3-dimensional visualisation of the axis is extremely helpful. Malalignment of the sagittal or transversal axis can disturb knee kinematics considerably [1, 12].

In order to decrease radiation exposure for navigated surgery, pivoting algorithms are used to calculate the centre of the hip. Factors like limited range of motion of the hip, obesity of the patient, non-spheroid femoral head, severe dysplasia or other anatomical abnormalities of the hip joint limit the availability to assess the hip centre [8]. However, many surgeons use pivoting algorithms to calculate the centre of the hip, in particular because it does not require radiation, and because pivoting is easier to apply than fluoroscopic analysis [22]. The accuracy of pivoting algorithms in comparison to fluoroscopical method is still in discussion [21, 24].

For registration of the ankle centre percutaneous digitalisation of landmarks is available. This method does not require radiation and is easier to apply [14, 25]. If patients are too obese to palpate the malleoli exactly, or if a deformity exists at the ankle joint, percutaneous digitalisation is inaccurate and fluoroscopic landmark reconstruction recommendable [8].

A disadvantage of navigated analysis is the need for extra operative time, e.g. for the implantation of the reference bases and landmark registration. However, better and continuous visualisation of the axis by navigation helps to reduce the time of the entire operative procedure, and contribute to improved accuracy and clinical result.

Furthermore, the accuracy of navigated analysis depends on the stability of the dynamic reference bases. In case of unnoticed manipulation of the dynamic reference bases during surgery, the measurements are not correct any longer. Therefore, the surgeon should be aware of potential errors and convert to conventional measurement in case of any doubt. Another possible source of error is inaccurate manual definition of points after acquisition of fluoroscopic images. Digital circles and rulers of the navigation system try to solve this problem. Potential complications of the implantation of the half pins are infections of pin tracts or fractures through pin tracts.

Navigation systems increase the accuracy of the intraoperative analysis of alignment and provide continuous 3-dimensional assessment of the frontal, sagittal and transversal axis. Future clinical studies have to prove the effect on long-term clinical outcome.

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