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Improving surgical precision – application of navigation system in orthopedic surgery

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Navigation systems track objects with precision expressed as root mean square equalling even up to 0.15 mm. Application of navigation system combined with imaging technique makes surgical operations less invasive, which results in the reduced risk of infection, smaller scar and a shorter time of rehabilitation. Imaging techniques allow surgeon to create individual virtual models for virtual surgery planning. Navigation system tracks the positions of surgical tools in relation to the patient's coordinate systems. Medical imaging enables low-invasive surgery, whereas the position of surgical instruments is monitored on screen.

The paper presents a newly developed computer-aided surgical system consisting of ultrasonographic probe and tracking system to measure bone geometry, design surgical scenario virtually and follow it intraoperatively. The system assists surgeon to correct bone deformities. The paper presents the results of several accuracy tests, which demonstrate good repeatability and accuracy.

Key words: *biomedical engineering, computer-aided surgery, sonography, computer navigation*

1. Introduction

Computer-aided surgery is a technique allowing both high precision and smaller invasiveness, which result in shorter rehabilitation of the patient who has underwent operation. The advantages of this approach encourage surgeons and engineers to adapt this technique to various treatments. Orthopedic operations as very precise procedures take advantage of such high technologies as medical imaging and tracking systems. Nowadays in orthopedic surgery planning, the analysis of long-standing radiograms in the anterior–posterior and lateral projections is still a standard method. Based on this data set it is possible to design deformity correction and to approximately predict its results. The deviation of mechanical axis in two planes is evaluated, and the point of deformity correction (the so-called Center of Rotation Angulation (CORA)) is calculated (figure 1) [15]. The angles describing the deformities and deviations of mechanical axes are calculated. During the planning procedure, surgeon designs the position of osteotomy plane to provide the values of angles on a healthy side or the physiological values known.

Geometrical procedure designed on the basis of radiograms cannot exactly be followed during a real surgery without applying any navigation system. In these circumstances, any movements of the patient on a operating table are not considered, and landmarks positions cannot precisely be evaluated. DIGIOIA [5], [6] reports that if one relates the position of surgical instruments to the plane parallel to operating table, serious complications may arise. An improper align-

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ment leads to the malfunction of lower limb: abnormally distributed load, which determines the process of bone adaptation [1], [13]. Even a few degree deviation of the mechanical axis of bone significantly increases the risk of complications [9].

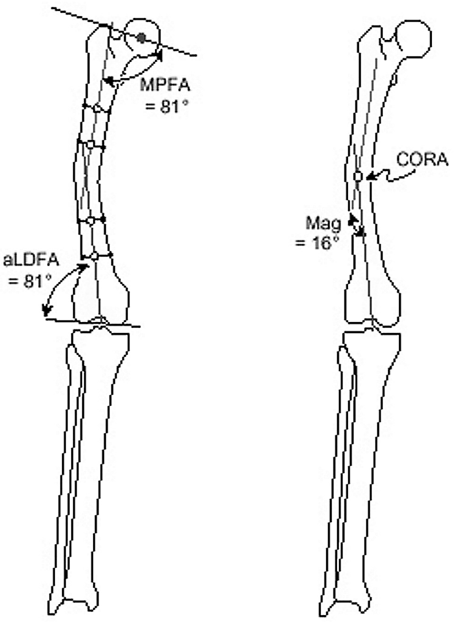


Fig. 1. Planning of CORA for deformed femur stem correction [14]

DiGioia proposes an anatomical plane, defined by landmarks, to perform precisely a hip arthroplasty. The position of the anatomical plane is tracked continuously, if the localizer controls the position of the sensor mounted in the patient body.

This paper describes the concept of computer-aided surgery, with a special attention paid to image-aided surgery and its mathematical fundamentals. The existing systems applying sonographic imaging and the innovative system were overviewed. However, the crucial part of the paper deals with ultrasound-aided computer surgical system developed by the authors. The accuracy tests based on various phantom constructions are described in section 3.

2. Material and methods

2.1. Computer-aided surgery

The primary task of tracking systems is to lead an object to a target. Medical navigation system localizes surgical instruments and allows their proper location in the patient body. Acoustic (for example, ultrasonic), optical and electromagnetic tracking systems are applied to computer-aided surgery. Nowadays popular localizers are produced based on optical and electromagnetic technologies. Electromagnetic method requires electromagnetic field transmitter, which generates local magnetic field. Magnetic sensors identify the position of instrument. Distortions introduced by metallic objects and electromagnetic devices are considered to be the main disadvantage of magnetic navigation. This method, however, has a significant advantage, i.e. a high resolution.

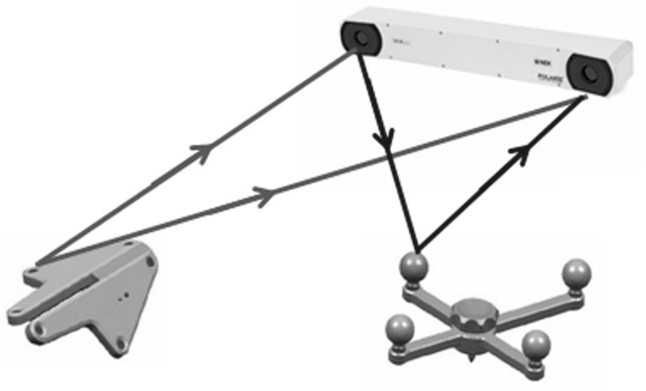


Fig. 2. Polaris NDI Tracking Navigation System with active and passive Rigid Bodies

Optical technologies are reasonably priced, high-resolution systems. However, the functioning of optical localizer may be disturbed by reflective objects and external sources of IR light. Infrared cameras localise active or passive elements, the so-called Rigid Bodies (RB), objects with constant geometry – constant distances between important points of these structures (figure 2). Active markers have been built in diodes emitting infrared light registered by camera. Passive markers contain balls reflecting IR emitted by special IR emitters mounted in camera. In both cases, the infrared light registered enables localization of Rigid Bodies in space: rotation and translation from the camera coordinate system into the marker coordinate systems [7].

The system calculates the position of transmitters and reflectors in space. The position of one Rigid Body can be related to the camera coordinate system (figure 3). The other way is to track one sensor in relation to coordinate system of the second sensor. In the operating room, the infrared diodes or reflecting balls are attached to surgical instruments and the patient's body. The position of the instrument tip is defined in the patient coordinate system.

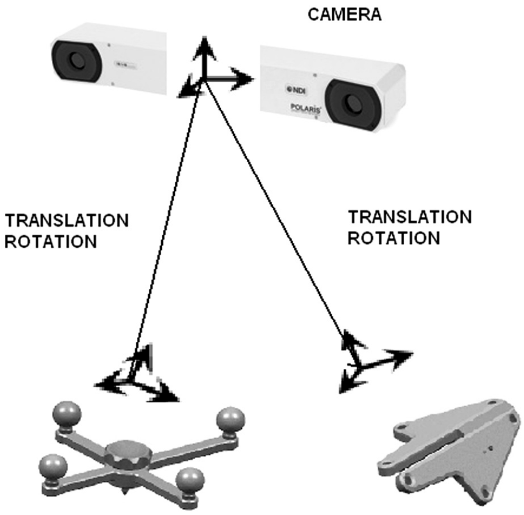


Fig. 3. Camera coordinate system working as reference coordinate system

2.2. Mathematical apparatus for navigation system

Navigation system transfers the transformation matrix from camera coordinate system into coordinate system of a navigated Rigid Body. The transformation matrix, consisting of the translation vector (T) and the rotation matrix (R), transforms the camera coordinate system into the Rigid Body coordinate system.

$$\text{Transform\_matrix} = \begin{pmatrix} R_{11} & R_{12} & R_{13} & T_{14} \\ R_{21} & R_{22} & R_{23} & T_{24} \\ R_{31} & R_{32} & R_{33} & T_{34} \\ s1 & s2 & s3 & 1 \end{pmatrix}.$$

The $s1$–$s3$ elements specify scaling and aberrations of camera.

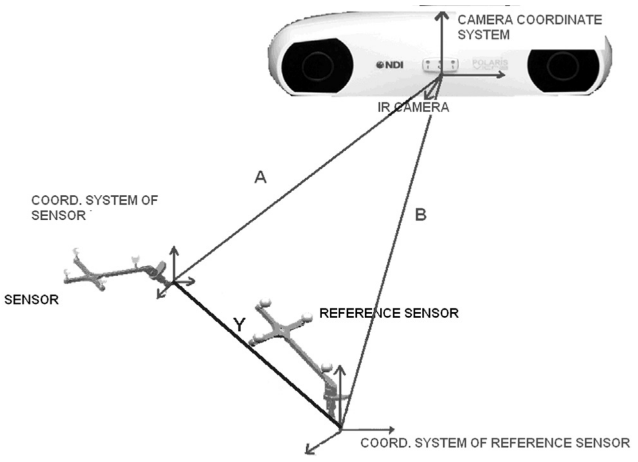


Fig. 4. Reference coordinate system combined with one of Rigid Bodies

In order to define the position of one marker in the coordinate system of the "reference marker", the transformation matrix Y (see figure 4) is calculated according to the following formula:

$$A \cdot Y = B,$$
$$\rightarrow Y = A^{-1} \cdot B,$$

where A and B define the transformation from the camera coordinate system into the Rigid Bodies' coordinate systems.

2.3. Image-aided computer-assisted surgery

In image-aided and image-free computer-assisted surgeries, it is necessary to mount a reference Rigid Body in the patient's body to track his/her position on the operating table. Obviously all important surgical instruments must be equipped with navigation sensors to track their positions in relation to the patient's coordinate system.

In an orthopedic image-aided computer-assisted surgery, standard imaging techniques are fluoroscopy and CT-scans. Computed tomography provides high-quality images of bone; however, one must be aware of the projection errors [18].

Image-aided navigation enables both planning and interactive intra-operative measurement with a simultaneous visualization of surgical instrument positions on a screen. A planning procedure consists of the following phases: image-based reconstruction, cutting design and selection of implant size, its localization and orientation in reconstructed anatomical shape. To follow the surgical scenario designed, e.g. to apply pre-operatively collected image data, its fusion with intra-operative data is required. The algorithm of fusion (matching) determines the transformation matrix that allows the pre-operatively registered image dataset to be transformed into intra-operative dataset. Input data for the algorithm are coordinates of intra-operatively palpated landmarks and the corresponding points on the pre-operative images. After the registration is performed, the patient's position is permanently tracked during the operation, and the position of instrument tip in relation to a reconstructed bone can be visualized on the screen.

Image-aided navigation is a complicated and time-consuming procedure. Nevertheless it must be stressed that only image-aided systems apply individual patient's anatomy data and control instrument tip in relation to the collected dataset of medical images.

2.4. Ultrasound navigated system for osteotomy planning

CT/fluoroscopy-aided surgical systems require an expensive and harmful imaging technique. Our aim was to apply ultrasonographic imaging in the computer-aided orthopedic surgery. The main advantages of ultrasonography are as follows: non-invasiveness, intra-operative access and approximately real time imaging. Although ultrasonography is not readily applied in bone examination, since ultrasounds have a limited ability to "be transmitted inside the bone tissue", a hyperechoic structure is visible on a sonographic scan. The returning echo is produced by a soft tissue–bone border with significant difference in acoustic impedances.

The systems equipped with ultrasonographic device are mainly applied to identify the landmarks on ultrasonic scans [12]. The definition of landmark positions is more precise than palpation, especially in the case of obese patients. Ultrasound probe enables the assessment of the pelvic landmarks [11, 14]. The ultrasonographic imaging technique is applied to register another image datasets, for example, MRI data. This approach enables a high-quality MRI dataset to be applied intra-operatively [4].

The existing computer-aided surgical systems containing sonographic freehand imaging were analyzed. One of them, similar to that described in this paper, was developed by Bovio et al. [2]. The system has been applied in bone reconstruction prior to a total knee replacement. The accuracy of the reconstruction obtained during testing on cylindrical phantom (mimicking bone shape) equalled 0.6 ± 0.39 mm.

The paper presents a newly developed system that combines an optical tracking system Polaris from NDI and portable ultrasound system EchoBlaster 128 from Telemed with linear probe of a central frequency equalling 5 MHz [8]. The ultrasound probe is equipped with the sensor enabling communication with navigation system (figure 5). It makes it possible to position the probe in space in relation to patient's reference coordinate system [17]. Using a proper calibration matrix (*C*), it is possible to specify the coordinates of each pixel of any scan registered in patient's coordinate system.

Our system is designed for universal application: it allows us to measure geometric parameters of bone, to reconstruct its surface shape and to construct a surgical scanario.

In figure 6, the procedure of anatomical landmark definition on the sonographic scans is presented. This procedure makes the femur length measurement possible. Femur head center is defined as an averaged point of semicircle centers fitted to the bone contours on at least two ultrasound scans. The distal point can be defined as the point in the notch between the femur condyles. The line connecting the femur head center and the distal point defines a three-dimensional length of femur bone.

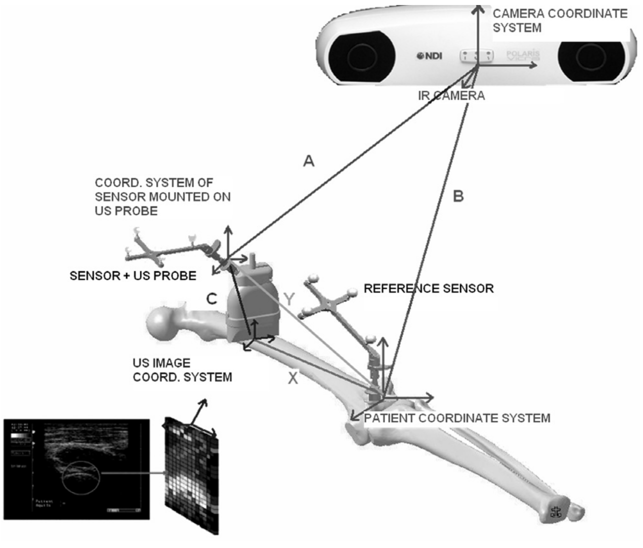
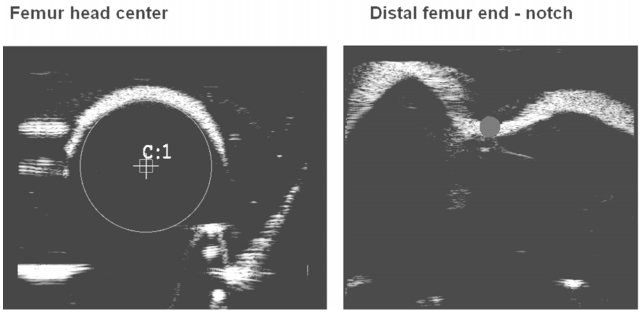


Fig. 5. Scheme of computer-aided surgical system based on ultrasonography


Femur head center

Distal femur end - notch

Fig. 6. Definition of femur length on ultrasound scans

In the second step, the shape of bone is reconstructed and the surgical procedure is designed. The necessary data is collected by ultrasound probe equipped with the sensor that communicates with the navigation system. The dataset is analyzed to define the cloud of points of bone contour and to reconstruct the shape of bone. Based on the ultrasound scans, after filtration eliminating spots, the bone contour is segmented. The segmentation technique makes use of the physical properties of bone imaging with ultrasonography [3]. Finally, a three-dimensional cloud of points is created and the shape of bone is reconstructed (figure 7).

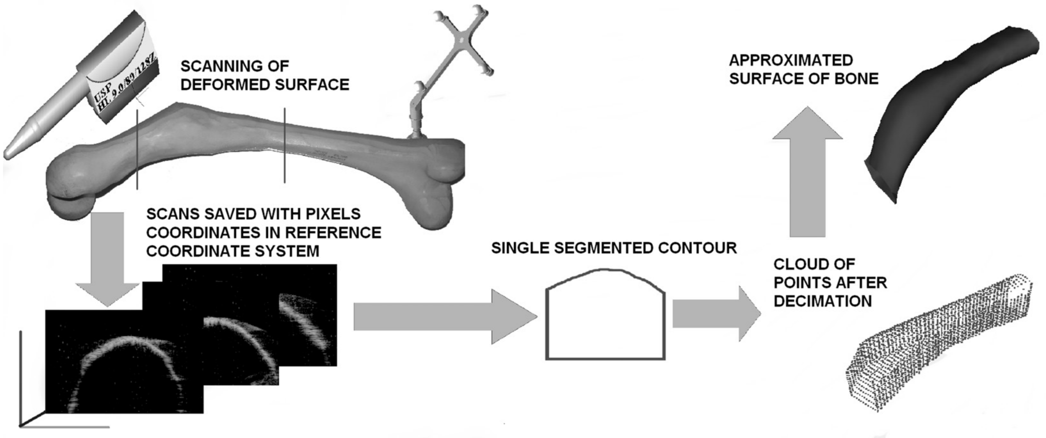


Fig. 7. Definition of bone contour on particular slides and 3D bone reconstruction

The model obtained is applied to planning a surgery. The osteotomy plane designed can be intraoperatively applied (figure 8).

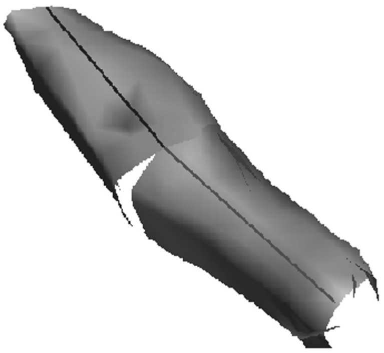


Fig. 8. Planning of osteotomy on 3D bone of reconstructed shape

3. Results

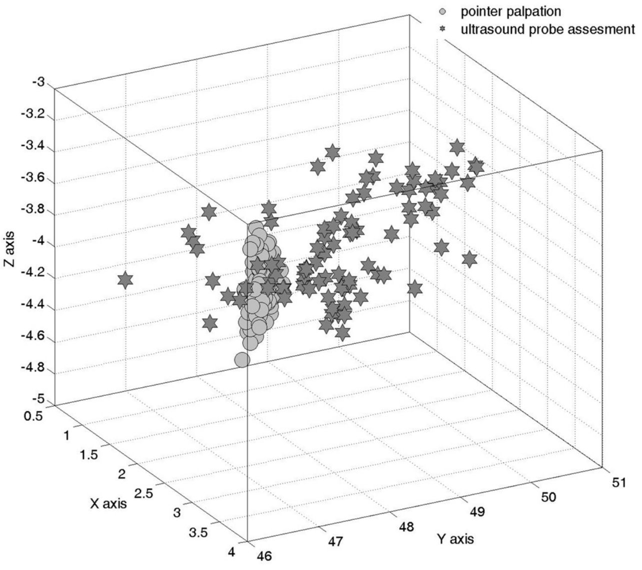
3.1. Accuracy test on phantoms

3.1.1. Test on phantom (two crossing threads) with mounted reference coordinate system

To test the accuracy of the system developed a phantom consisting of two crossing threads was applied. The phantom was put in water whose temperature reached 36 °C. The velocity of sound significantly depends on temperature.

There were registered one hundred scans visualizing the crossing point of two threads. On all the scans the position of the crossing point of threads was determined. The coordinates of the point were calculated in reference coordinate system mounted on the phantom.

The results of ultrasound probe assessment are related to the location of the crossing point of the threads found by a calibrated pointer-aided palpation. To palpate the landmark, the pivot algorithm was applied. The procedure calculates the shift between the coordinate system of Rigid Body mounted on the pointer and its tip. Localizer provides the position of sensor attached to the pointer, and the software applies to tip offset. The coordinates of palpated point were specified in the reference coordinate system mounted on a phantom.



Graph 1. Assessment of crossing point applying ultrasound probe and pointer

The results obtained are presented in graph 1. In order to evaluate the discrepancy between both datasets, the average values with standard deviation for each coordinate were calculated. Additionally, the

RMS error was calculated for the data assessed by ultrasound probe and pointer:

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2} \ ,$$

where:

$n = 100$ (number of measurements),

$\bar{x}$ – arithmetic average of measured points,

x_i – the i-th measured point.

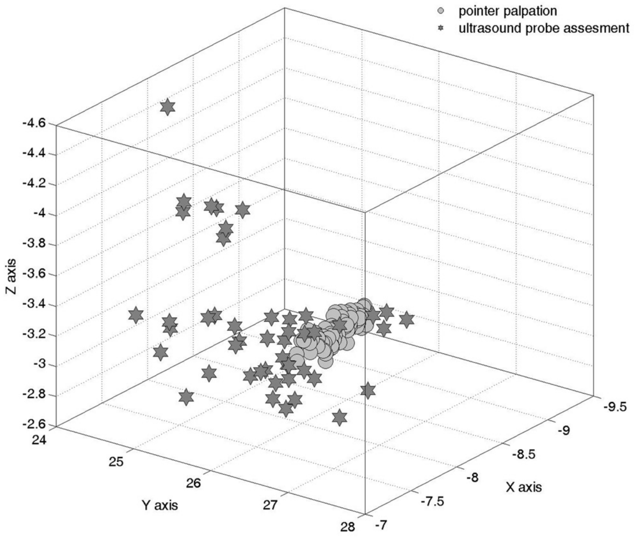
The palpation of the crossing point is the reference measurement, hence the *RMS* value is much lower than that obtained by ultrasound probe assessment. Nevertheless, the repeatability and accuracy of ultrasound system are high enough. The results are presented in table 1.

Table 1. Results of thread crossing point assessment by ultrasound probe and pointer

Fiducial crossing point of threads	Ultrasound probe assessment (mm)	Palpation by pointer (mm)
x-coordinate	2.30 ± 0.62	0.93 ± 0.10
y-coordinate	48.60 ± 0.89	48.56 ± 0.89
z-coordinate	–3.79 ± 0.30	–4.38 ± 0.14
RMS value	1.12	0.22

3.1.2. Test on phantom with two mounted cones, with palpable fovea

The application of thread phantom is not the best method for estimating the accuracy of determining a point on ultrasound image. Therefore, a phantom with two mounted cones was applied to find the position of their foveae by a pointer and to easily mark their position on a sonographic scan. As in the case of tests with crossing thread phantom, the phantom with cones is equipped with stabile rigid body determining the reference coordinate system for both datasets. The palpation by pointer was accurate and easy because of the construction of markers (cones). The position of fovea is also clearly seen on a sonographic scan (figure 9). The measurements for both foveae with pointer and ultrasonic probe were performed 50 times. Both datasets obtained are presented on a three-dimensional graph (graph 2).



Graph 2. Assessment of cone fovea applying ultrasound probe and pointer

Table 2. Results of cone fovea assessment by ultrasound probe and pointer

Fiducial cone fovea	Ultrasound probe assessment (mm)	Palpation by pointer (mm)
x-coordinate	–7.87 ± 0.33	–8.83 ± 0.19
y-coordinate	25.66 ± 0.92	25.45 ± 0.05
z-coordinate	–3.24 ± 0.38	–2.87 ± 0.04
RMS value	1.04	0.19

The values of *RMS* smaller both for pointer palpation and ultrasound assessment than those in the case of thread crossing point phantom were observed. This proves that the selection of phantom influences the accuracy validation.

3.2. Ultrasonic 3D phantom from CIRS company

To test the accuracy of a reconstructed shape a calibrated three-dimensional phantom made of Zer-

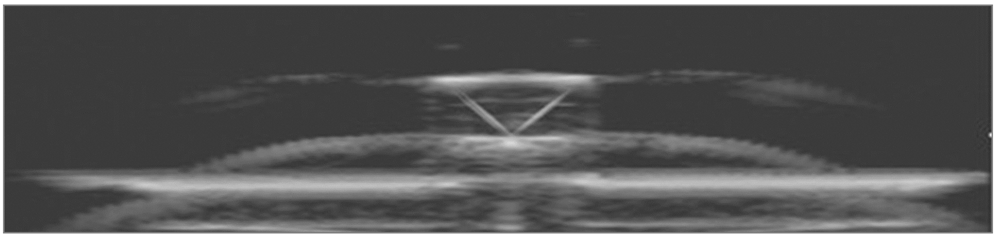


Fig. 9. Cone observed on ultrasound image

dine® material (water-based elastic polymer) with the absorption rate of 0.50 dB ± 0.05 dB/cm/MHz and the speed of sound of 1540 ± 6 m/s was applied. The phantom comprised two volumetric objects whose speed of sound of 9 ± 3 dB was lower than that of background. The objects exist 2–6 cm beneath the surface scanned. The ellipsoid objects are precisely calibrated by the manufacturers [16].

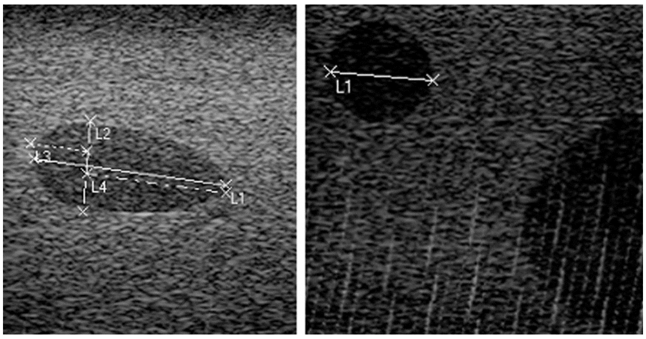


Fig. 10. Tests of accuracy on CIRS three-dimensional phantom

To test the objects the long (*A*) and short (*B*) axes of ellipsoid were measured. A short axis is the radius of the volumetric object in a perpendicular intersection. The parameters were measured ten times. The proper dimensions and the values obtained are presented in table 3.

Table 3. Measurement of system accuracy applying "volumetric" phantom built of Zerdine®

Parameter	Value	
	Nominal	Measured
A	39.0 mm	38.0 mm±0.45 mm
B	18.0 mm	16.6 mm±0.72 mm

The results obtained testify to a high accuracy of the system itself. It should be stressed that marking the landmark positions on the ultrasound images of this particular phantom is very useful. The border between a volumetric object and the background is characterized by a strong contrast, which results also in a higher repeatability of measurements compared with that of the two phantoms previously measured.

4. Discussion

The system described combines ultrasonography with computer navigation to measure a bone geometry, to design the surgery, and to follow the surgical scenario intra-operatively. It is difficult to compare this method with the existing techniques based on ultrasonographic imaging. First of all, it is a universal measuring system, enabling measurements according to self-defined templates. The system developed, as inapplicable to registering MRI or CT datasets by means of ultrasonographic imaging, is entirely based on sonography, e.g. the pre-operative and intra-operative image datasets are collected by ultrasonic probe. Ultrasonic measurements are noninvasive and repeatable; however, they have to be carried out by an experienced physician. The most difficult problem is a proper alignment and pressure of ultrasound probe on skin which enables an accurate bone contour to be registered.

The system presented by Bovio et al. [2] is similar to ours. Its accuracy can be related to that based on 3D calibration phantom. The comparison of the results obtained by Bovio et al. and our team reveals that standard deviations of the lengths of the axes measured are similar.

The application of ultrasonography poses a considerable but exciting challenge. However, the advantages of this imaging technology encourage us to use it for computer-aided navigation. The tissues (for example, bone) identified on ultrasound scans can be spatially reconstructed. The future of sonography is promising; the sonographic equipment is developed and the quality of images is still improving. The investigation described in this paper shows that the important problems to be solved are: tissues differentiation, elimination of artefacts and optimal software development.

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