A New Experimental Measurement and Planning Tool for Sonographic-assisted Navigation

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abstract

In this study, we present a new 2.5-dimensional ultrasonic navigation system for measuring axes, lengths, and torsions preoperatively, intraoperatively, and postoperatively. The system comprises an ultrasound unit with a 5-MHz linear probe (TELEMED Echoblaster 128; Telemed, Vilnius, Lithuania) and a navigation system (OrthoPilot; B. Braun Aesculap, Tuttlingen, Germany) with a Polaris camera (Northern Digital, Waterloo, Canada). Specialized software developed for this application allows for selecting any body region on a virtual 3D skeleton. With a virtual ultrasound probe, planes needed for measurements can be defined. For each section, the respective surface contour of the bone, which is also shown in the ultrasound image, is displayed. Alternatively, the clinician can use established standard sections. Finally, the required length, axes, and torsions are defined. The accuracy and precision of the system were tested using a plastic model. The measurements of length, torsion, and axis values were accurate to -0.1 ±0.3 mm (95% CI), 0.1°±0.2° (95% CI), and 0.0°±0.006° (95% CI), respectively. The precision variances for length, torsion, and axis were 1.17 mm (standard deviation) and 0.94° and 0.66°. These results suggest that the new sonographic method is more accurate than conventional radiographic techniques.

In the conventional radiologic determination of the skeletal geometry, 3-dimensional (3D) bone structures are represented as 2D film images. Consequently, different projection errors occur as a function of the position of the x-ray tube. Often, a precise representation of a bone in two planes is not possible due to limitations in positioning the patient and the subjectivity of the manual settings of the imaging system. This makes precise scanning of sections of the skeleton difficult.[1]

Intraoperatively, the surgeon must rely on image converters to visualize bone contours. The new 3D converters may allow a volume representation, however, with the edge length of the image cube limited to 12 cm. Such methods are, therefore, unsuitable for measuring the geometry of larger bones.[2]

With the introduction of the spiral computed tomography (CT) technology, exact 3D representations and measurements of the human skeleton became possible. However, this technology cannot be used intraoperatively.

Previously, 2.5D ultrasound had been an established tool for preoperative and postoperative diagnosis.[3] A disadvantage of 2.5D systems was that precision is affected by air flow and temperature fluctuations.

These problems were resolved by integrating a 2D ultrasound unit (TELEMED, Echoblaster 128) into the OrthoPilot navigation system (B. Braun Aesculap, Tuttlingen, Germany). This project attempted to develop a universal ultrasonic measuring and planning system that allowed surgeon to obtain 3D measurements on any sonographically scannable region of the skeleton and to plan a corrective osteotomy.

MATERIALS AND METHODS

The hardware consists of an ultrasound unit (TELEMED Echoblaster 128) with a

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Dr Keppler is a member of the B. Braun Aesculap speaker's bureau. Dr Gebhard has no financial relationships to disclose. Kozak is an employee of Aesculap. Krysztoforski, Swiatek, and Krowicki have received financial compensation from Aesculap in the last 12 months. Pinzuti has received financial compensation from B. Braun Aesculap.

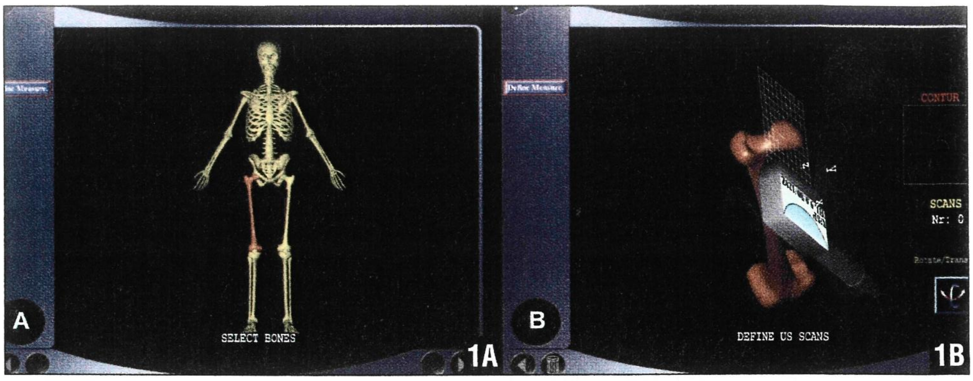

Figure 1: Selecting the skeleton regions to be measured (A). The virtual ultrasound probe is used to define any ultrasound scan. The respective surface contour is displayed simultaneously (B).

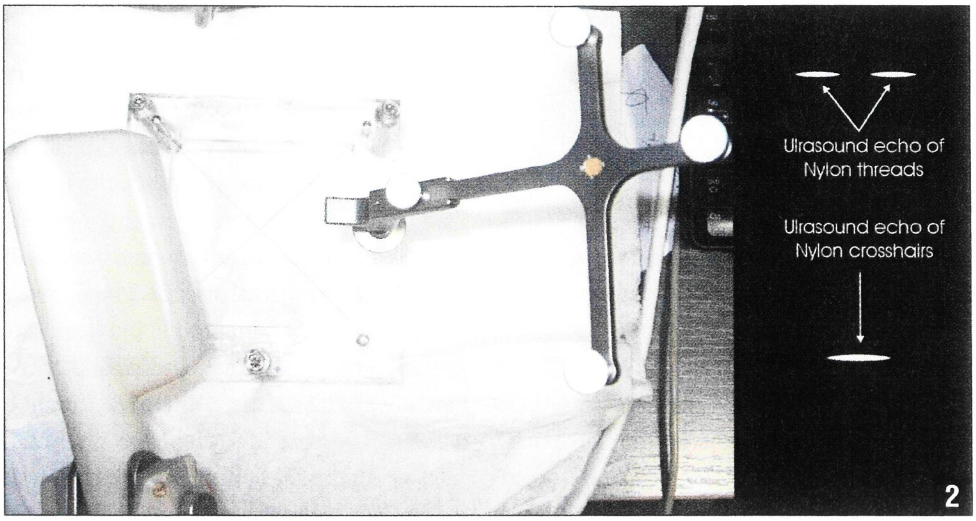

Figure 2: Set up for determining the precision of the new 2.5D ultrasonic measuring system. Two nylon threads are crossed in a plain water bath. The ultrasound image clearly shows the threads and the crossing point.

5-MHz linear probe and a video-optical localizer (Polaris; NDI, Toronto, Canada) with active or passive rigid bodies. The arrangement of the transmitters allows for recognizing the calibrated ultrasound probe in any spatial position. Thus, it is possible to assign x, y, and z coordinates to any sonographically scannable landmark and to perform 3D measurements as in a spiral CT scan.

The software components used in the study were C++, OpenGL (Silicon Graphics, Sunnyvale, Calif), DirectX and DirectShow (both Microsoft, Redmond, Wash), combined with the OrthoPilot user interface.

The program begins by registering patient data, which can be exported as MS Excel files.

The user then selects a predefined measurement or defines his or her own measurement by selecting a given bone (eg, femur) (Figure 1A).

The selected region is then displayed with an enlargement factor. Subsequently, the respective scans are defined using a virtual ultrasound probe, and simultaneously the surface contour of the bone, as visualized in the ultrasound image, is displayed (Figure 1B).

After the required sections have been defined, the anatomic landmarks are defined on the sonographic images. For this purpose, the system offers point, circle, and line selections. There also is the option to define a point by several sections, which improves the reproducibility of the measured points.

The virtual bone can be hidden at any time to obtain a better overview of the defined points. The selected points are then used to compute any distances and angles and can be projected on different planes.

In the next step, sonographic measurements are obtained. The program prescribes the sequence of the defined ultrasound scans including the bone structures of the virtual skeleton. A report of these measurements contains patient data, scan definitions, and measured length.

Because the user can define any scan, the program allows measuring lengths and angles in any region of the skeleton. Either the infrared camera or a reference triangle (rigid body) can be selected as reference. If the camera is chosen for reference, the system is movement-sensitive during the sonographic examination. If a rigid body is used, the system is insensitive to movement, provided the rigid body is fixed directly on the bone.

The precision of the new measuring system was initially assessed using a plain water bath and two perpendicular crossed nylon threads. The known coordinates of the crossing point were then compared with the coordinates determined with the sonographic images (Figure 2).

The accuracy and precision of measurements produced by the system were investigated using a plastic leg model, which was manufactured with a computer numerical control mill with a tolerance of max. 0.5 mm. Length, axis, and torsion can be adjusted in the model (Figure 3). To ensure realistic test conditions, the ultrasound probe and plastic surface were coupled with a silicone pad. The ultrasound probe was held by hand above the respective measuring point, and length, axis, and torsion angle were each measured.

RESULTS

A total of 50 repeat measurements from various positions to determine the location of the nylon cross-hairs in the plain water bath yielded an average deviation of 0.8±0.7 mm (SD), with a maximum deviation of 2.0 mm.

Accuracy to -0.1±0.3 mm (95% CI) was obtained for the measurement of model leg length between 834 and

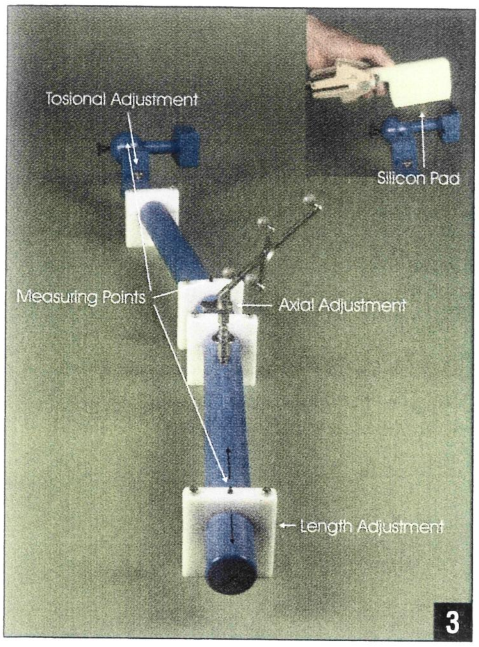

Figure 3: Model for testing the accuracy of the new universal ultrasound measuring system. The model allows for adjusting length, torsion, and axis of the leg in its clinically relevant sections to any chosen position. The ultrasound probe is coupled to the plastic leg via a silicone pad.

848 mm. The precision of the measurements, calculated in the mixed model, was 1.17 mm (SD), with a maximum deviation of 2.8 mm (Figure 4).

Torsion angles between 0° and 50° have been determined with an accuracy of 0.1°±0.2° (95% CI). The precision of the measurements according to the mixed model was 0.94° (SD), with a maximum deviation of 2.12° (Figure 5).

The measurements of the mechanical leg axis (mFTW) on the model between 170° and 190° showed an accuracy of 0.0°±0.006° (95% CI). The precision as calculated with the mixed model was 0.22° (SD), with a maximum deviation of 0.66° (Figure 6).[1]

DISCUSSION

Knowledge of bone geometry is essential to carrying out corrective osteotomies. The goal of fracture therapy as well as of implantation of artificial joints is to achieve an exact reconstruction of the original anatomy, including correct leg length, axis, and torsion.[4]

Preoperative diagnostic equipment with navigated ultrasonic measurement capabilities to determine leg geometry have been established at some centers.[3] A disadvantage of previous systems was that they were useful for evaluation of the lower extremity only and to exclusively preoperative and postoperative applications. With the new ultrasonic measuring device combined with the OrthoPilot platform, however, any bone that can be visualized sonographically can be scanned and measured in three dimensions. When a reference frame can be fixed to the bone, the method is not sensitive to movement. In other cases, where such a rigid connection is not possible, the infrared camera can be used as an alternative reference device.

The validity criteria for any measuring device are the accuracy and precision of the measurements obtained.[5] Accuracy is the degree of agreement between expected measured value and actual measured value. For the ultrasound method presented in this study, the accuracy for measuring the leg length is -0.1±0.3 mm (95% CI). In a phantom study, Clark et al[6] cites ±3 mm as the maximum deviation of the accuracy achieved with teleradiography. For the computed-tomography measurement of the leg length on a model, the study by Carey et al reports a maximum error of ±2 mm, whereas Aaron et al cite a standard deviation of repeated measurements of 0.8 mm.[7,8] These figures exceed results achieved with the ultrasound method presented in this article.

Computed tomography is still the gold standard for determining the femur torsion angle. The accuracy and precision achieved with CT is reported in the literature as between 1.2° and 3.2° on macerated bone.[9-11] With the new ultrasound method, accuracy is 0.1°±0.2° (95%) and precision is 0.94° (SD). It must be considered that the contours used for measuring torsion are defined more clearly in a plastic model than in cadaveric bone. However, the new 2.5D sonographic method is at least equal to CT with regard to accuracy and precision.

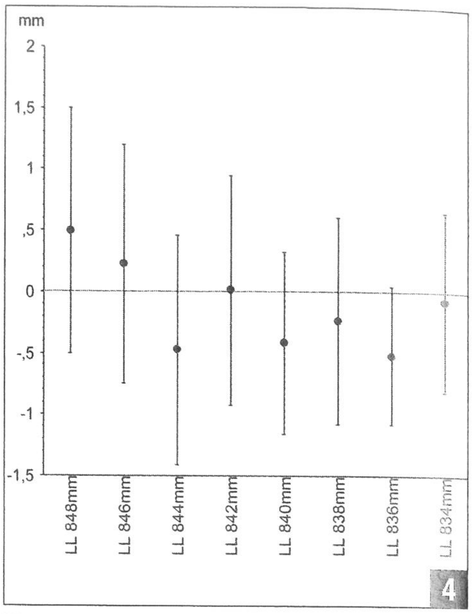

Figure 4: Variation of the results from 10 repeated measurements of leg lengths (LL) between 834 and 848 mm: 95% CI with mean values (•).

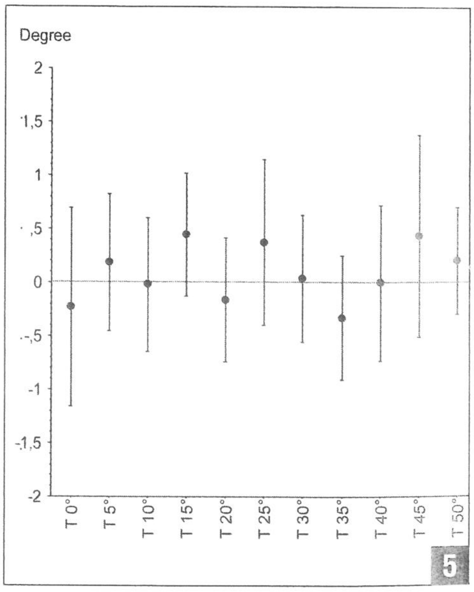

Figure 5: Variation of results of 10 repeated measurements each of torsion angles (T) between 0° and 50°: 95% CI with mean values (•).

Another critical factor for the bone geometry scan is axis measurement. For this task, long-leg x-rays to determine the mechanical leg axis is standard.[12]

As measurements on a phantom leg with the knee in 10° flexion have shown, the projected leg axis on the X-ray changes by one degree while rotating the leg by 10°-15°.[13] The new ultrasound method

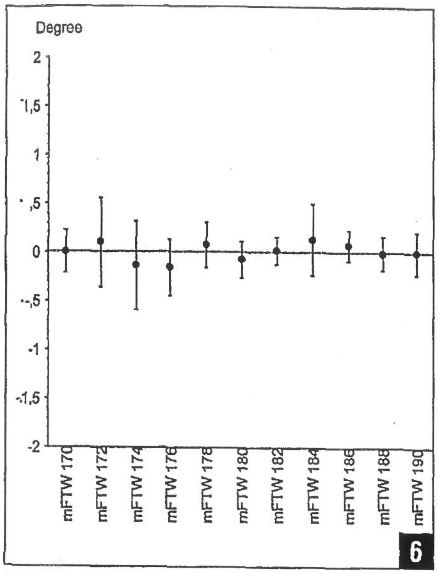

Figure 6: Variation of the 10 repeated measurements each of the mechanical leg axis (mFTW) from 170° to 190°: 95% CI with mean values (•).

presented in this article is carried out independent of the leg position. As long as the rigid body is solidly fixed to the leg, the system is also not affected by rotational movements during the measurements. The 95% CI for this method is ±0.006° when measuring the leg model, and the standard deviation for the precision is 0.22°. This means the new ultrasound method is more accurate and precise than the existing radiological technique for determining mechanical leg axis.

It must be considered that the precision of the new ultrasound method was based on measurements of a leg model, and that the clinical condition was simulated to an extent by using a silicone pads. The precision of the new method definitely depends on clinical conditions and the skill of the clinician carrying out the measurements. As reported in a study by Keppler at al,[3] measurements with a 2.5D ultrasonic measuring system produced the same results for lengths and torsions in the lower extremities as measurements obtained through CT scans in 1999. However, the new ultrasonic measuring system presented in this article is comparable with the system used in 1999 due to improvements in technology. It has to be expected that its precision in measurements will be significantly superior to the precision of the old system. On the other hand, the precision will also depend on the available landmarks that can be scanned through the sonographic technique and, consequently, from the body region to be scanned. Additional clinical studies are needed to clarify these points.

CONCLUSION

It can be concluded that the new 2.5D ultrasonic measuring system is more accurate than conventional radiographic techniques. The primary advantage of this method compared with computer tomography is that measurements can be performed preoperatively, intraoperatively, or postoperatively. This will be the ideal to the orthopaedic community for planning corrective osteotomies or assessing geometric parameters of the skeleton after prosthetic implantation. ◙

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