# Application of Navigated Ultrasound for Assessment of the Anterior Pelvic Plane in Patients With Degenerative Hip Diseases

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***Objectives***—Correct positioning of the acetabular cup is the key for successful total-hip replacement. In common clinical practice, the target alignment of the cup is defined with respect to the anterior pelvic plane. In patients with substantial anterior pelvic plane inclination, this condition may lead to inappropriate distribution of the load on the cup, as most of the forces exerted within the hip joint act along the vertical axis. With the known pelvic inclination, it is possible to readjust the position of the cup with respect to the individual posture of the patient. In this work, we present the first clinical evaluation of a new approach to measurement of the pelvic tilt angle using navigated ultrasound.

***Methods***—In our method, the ultrasound probe is tracked with an optical localizer implemented on a handheld mobile device. The method was tested by taking preoperative measurements from 20 patients with osteoarthritis in standing, sitting, and supine positions.

***Results***—The mean values of the measured angles were consistent with the corresponding results reported by other authors.

***Conclusions***—Considering the noninvasiveness of the method and affordability of the hardware used in our system, it can be used in preoperative and postoperative measurements of pelvic orientation for supporting surgery planning and evaluation of treatment outcomes.

***Key Words***—computer-assisted surgery; hip osteoarthritis; musculoskeletal ultrasound; total-hip replacement; ultrasound imaging

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**Abbreviations**
*THR, total-hip replacement; US, ultrasound*

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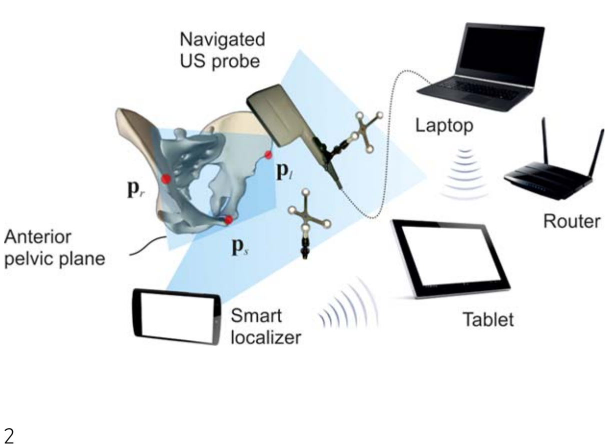
Despite being a treatment of choice in advanced degenerative hip diseases, total-hip replacement (THR) is associated with many complications, such as infections, luxation, and dislocations, with the latter having an incidence of up to 21%.[1] One of the factors that increases the risk of dislocation is positioning of the acetabular cup.[2] In 1978, on the basis of radiographic measurements, Lewinnek et al[3] defined a safe angular range for cup placement as $15° \pm 10°$ of anteversion and $40° \pm 10°$ of inclination. In subsequent research, a few parameters were proposed to quantify pelvic orientation and to facilitate correct positioning of the cup. The most important of these are the pelvic tilt angle, sagittal balance, and sacral slope. For these parameters to be clinically useful, one needs a reliable measurement method.

In the common approach, the position of the pelvis is assessed by radiographic methods,[4] but using these techniques raises the question of unnecessary exposure of patients to x-ray radiation. Another possibility is to determine the position of the pelvis by palpation of bony landmarks, either with a navigated pointer[5] or a digitizing arm.[6] The disadvantage of this method is that the accuracy of palpation relies on the experience of the clinician, and it may give misleading results in obese patients.[7] The pelvic angle has also been assessed cinematically by recording the trajectories of skin-affixed markers during gait[8] and predefined motion.[9] However, the practical importance of kinematic measurements remains debatable, as some authors suggest a satisfactory correlation between the position of the pelvis at standing and during gait.[10] The common shortcoming of all of these approaches is that they involve advanced technologies, so their cost may be considered disproportionate to their intended task, which is to determine a single angular value.

As an alternative to the above methods, Kiefer and Othman[5] proposed a technique called navigated ultrasound (US). In navigated US, the landmarks are visualized with US and localized according to the position of the probe. Originally applied to measurements of leg bones, it proved to be comparable to computed tomographically based measurements in terms of both accuracy and repeatability.[10] In contrast to the other methods, it is noninvasive and invariant to the patient's anatomy. However, it still fails to address the issue of high cost because an expensive optical localizer is required for probe tracking.

The aim of this work was to evaluate a new noninvasive method for measuring the pelvic tilt angle in standing, sitting, and supine positions and to apply it in everyday clinical practice for preoperative planning in THR. The method is based on navigated US and solves the problem of affordability by using easily available mobile devices: a smartphone as a localizer and a tablet as the main control panel of the measurement system. Up to now, in the experiments on phantoms, it has shown average angular tracking error of 0.5° and intraobserver repeatability within the range of ±0.7°.[11] This study is the first clinical evaluation of the method.

**Figure 1.** Main elements of the measurement setup.




## Materials and Methods

### *Patients*

This study was approved by the Bioethical Committee of the Medical University of Lodz, and all of the examined patients gave their written consent to participate in the study. Measurements of the pelvic tilt angle were done in a group of 20 patients in the Trauma and Orthopedic Department of the Hospital of the Ministry of Internal Affairs in Wroclaw. The inclusion criterion was unilateral or bilateral hip osteoarthritis with a radiologic score of 3 or 4 on the Kellgren-Lawrence scale. The group included 10 patients with degenerative changes of the left hip and 10 of the right hip. Five patients had already undergone arthroplasty on the other hip, and all of the patients had chronic pain. Patients with ankylosing spondylitis were excluded from this study. At the time of taking the measurements, the participants were hospitalized to have the THR procedure performed. The measurements were done no later than a few days before the surgery.

### *Measurement System*

The measurement system consists of a US system coupled with a laptop personal computer, a tablet, a smartphone, and a router (Figure 1). Additionally, the system uses 2 passive infrared transmitters (Aesculap AG, Tuttlingen, Germany) for tracking the US probe, the first mounted on the probe itself and the second used as a reference.

The images are captured by an Echo Blaster 128 US device (Telemed, Vilnius, Lithuania) with a 128-channel linear probe. The width of the beam and the scanning depth are both 80 mm. The probe is tracked by an optical localizer implemented on a Nexus 6 smartphone (Motorola, Libertyville, IL) using the device's calibrated rear camera and built-in light-emitting diode flashlight.[12] The main interface of the system runs on a

Tango tablet (Google, Mountain View, CA). The tablet application guides the operator through the measurement steps, displays the US image, and presents the measurement results. The interface module communicates with both the localizer and US module via a wireless local area network.

Using the navigated US probe, the operator measures 3 pelvic landmarks: the left and right anterior superior iliac spines and the pubic symphysis, denoted $\mathbf{p}_l$, $\mathbf{p}_r$, and $\mathbf{p}_s$, respectively. To find the real-world position of a specific point seen in the US image, the pixel coordinates of this point $(u, v)^T$ are converted to absolute length units by the formula

$$\mathbf{r}_i = \left( \frac{w}{U}u \quad \frac{d}{V}v \quad 0 \right)^T, \tag{1}$$

where $U$ and $V$ denote the height and width of the image in pixels, respectively. The position of the landmark with respect to the probe is found by translating it by a known constant vector, $\mathbf{t}_{i\to p}$ (Figure 2a):

$$\mathbf{r}_p = \mathbf{r}_i + \mathbf{t}_{i\to p}. \tag{2}$$

The reason for using the reference transmitter is that all 3 landmark points need to be measured in a consistent coordinate system. As a handheld device, the localizer does not provide a stable frame of reference, since it is usually moved between measurements of the subsequent points. Therefore, although the positions of both transmitters are initially measured relative to the localizer, the location of the probe transmitter is recalculated so that it can be expressed in the coordinate system of the reference. If we describe the originally measured locations of the probe and the reference transmitters by using transformation matrices, $\mathbf{T}_{US}^{L} \in \mathbf{R}_{4\times4}$ and $\mathbf{T}_{US}^{Ref} \in \mathbf{R}_{4\times4}$ (Figure 2b), the position of the probe in the reference coordinate system can be calculated as

$$\mathbf{T}_{US}^{Ref} = (\mathbf{T}_{Ref}^{L})^{-1}\mathbf{T}_{US}^{L}. \tag{3}$$

Finally, the real-world location of a specific point in the US image is found by calculating the coordinates in the probe's reference system by Equations 1 and 2 and then relating it to the reference transmitter by the transformation given in Equation 3. The positions of the pelvic landmark points obtained from the above computations are used to determine the anterior pelvic plane (Figure 3a). The plane is defined by a normal vector:

$$\mathbf{n} = (\mathbf{p}_l - \mathbf{p}_s) \times (\mathbf{p}_r - \mathbf{p}_s). \tag{4}$$

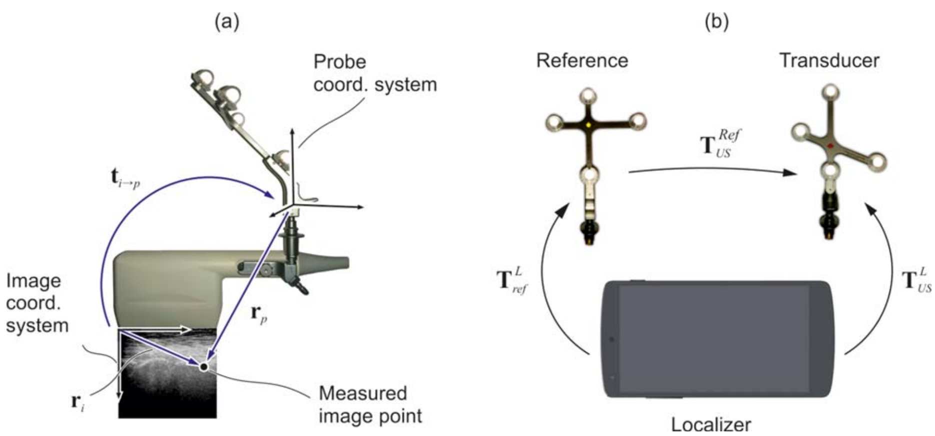
Combining $\mathbf{n}$ with the gravity vector $\mathbf{g}$ obtained from the smartphone's built-in accelerometer, the pelvic tilt angle is computed, as shown in Figure 3b, by the following equation:

$$\alpha_{PT} = 90^\circ - \arccos\left(\frac{\mathbf{n} \cdot \mathbf{g}}{|\mathbf{n}|\,|\mathbf{g}|}\right). \tag{5}$$

### *Measurement Procedure*

Measurements of the pelvic tilt were done by 2 physicians in a standard consulting room. After setting up the

**Figure 2.** Calculating the absolute position of a point indicated in the US image: **a**, position of the landmark point in the probe coordinate system; **b**, position of the probe coordinate system with respect to the reference transmitter.



system, the patient was put in the desired position, and the reference transmitter was placed in a way that allowed for tracking the US probe in a constant coordinate frame. The first physician tracked the probe with the localizer and operated the main application, and the other visualized the landmarks with US (Figure 4). A preview of the US image was displayed on the main interface of the system (Figure 5). To acquire a pelvic landmark, the operator of the US scanner swept the probe across the region where the landmark was expected to be found and identified the imaging plane that included the most protruded point of the anterior superior iliac spine or the center of the pubic symphysis. Once the location of the target point was marked in the image, the system calculated its real-world position by the method presented above and prompted the US operator for acquisition of the next point. After repeating this step for the remaining landmarks, the system calculated the pelvic tilt angle. The whole acquisition procedure took no more than 10 seconds.

The measurement tasks were split between the operators, since it was found that both visualization of the landmarks with the US probe and tracking of the probe itself with the smart localizer required a large amount of concentration and were equally important for accuracy. The US imaging requires a constant visual contact with the image to keep the target point within the imaging plane. Simultaneously, the smart localizer needs to be held at a minimum distance of 1 m from the transmitters, with both of them visible in the device's camera.

Although the physicians who were doing the measurements in this study were trained in medical US, the system can be also operated by a person with little experience in this imaging technique. As an aid for the

**Figure 3.** Calculating the pelvic tilt angle based on 3 pelvic landmarks: **a**, normal vector of the anterior pelvic plane; **b**, computing the angle between the anterior pelvic plane and the vertical plane.

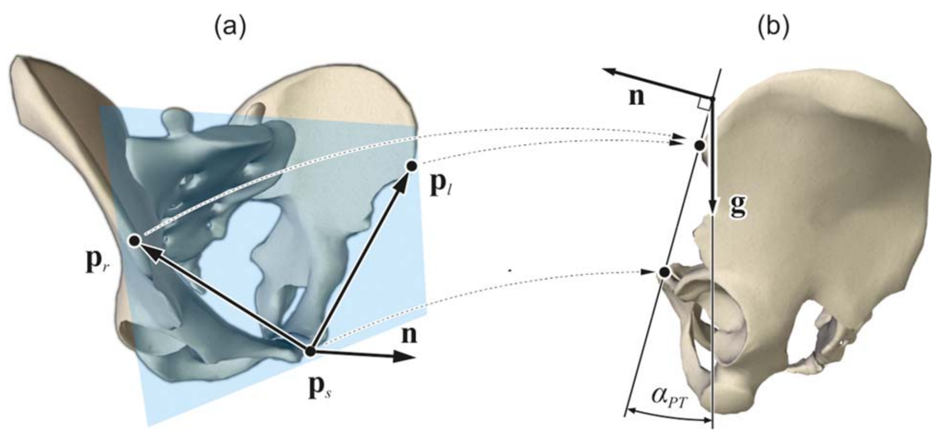
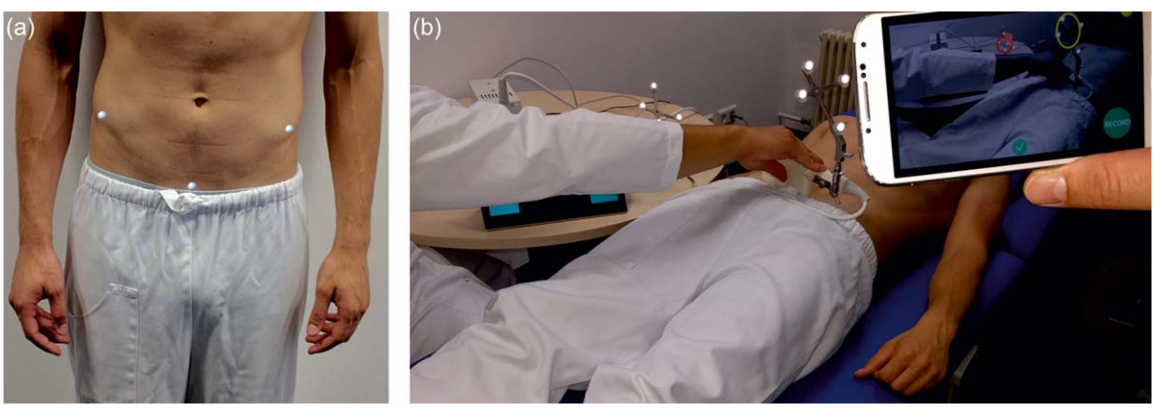



**Figure 4.** Overview of the measurement procedure: **a**, location of the bony landmarks of the pelvis; **b**, measurement in the supine position.



operator, an example US image of the target landmark is shown on the user interface of the tablet application, next to a live image obtained from the patient (Figure 5). With this example, it is easier to properly adjust the imaging plane and to find the target structure.

The measurements were done in supine, standing, and sitting positions, as these are the most important from the functional point of view. In the first part, the patients were lying supine on the examination couch, with arms and legs parallel to the longitudinal axis of the body, as shown in Figure 4b. For measurements in the standing position, the patients stood barefoot with their back against the wall, so that their backbone touched the wall without affecting their natural posture (Figure 6). The patients who had difficulties standing upright used a support handle, which helped them remain still during the measurement. The wall and the optional support prevented the pelvis from movement under the pressure of the US probe. In the third part of the examination, the patients sat on a chair barefoot and with their feet flat on the floor. In obese patients, this measurement was technically difficult because of the limited access to the pubic symphysis. Visualizing the pubic bone with US forced changes in the patient's position and affected the pelvic tilt angle. Therefore, the measurements in the sitting position were performed only for 14 patients.

**Figure 5.** Scanning of the landmark points and the corresponding US images: **a**, left anterior superior iliac spine; **b**, pubic symphysis. The target points are marked with a crosshair symbol. To the left of the live US scan obtained from the patient, the tablet application displays an example US image of the current target structure.

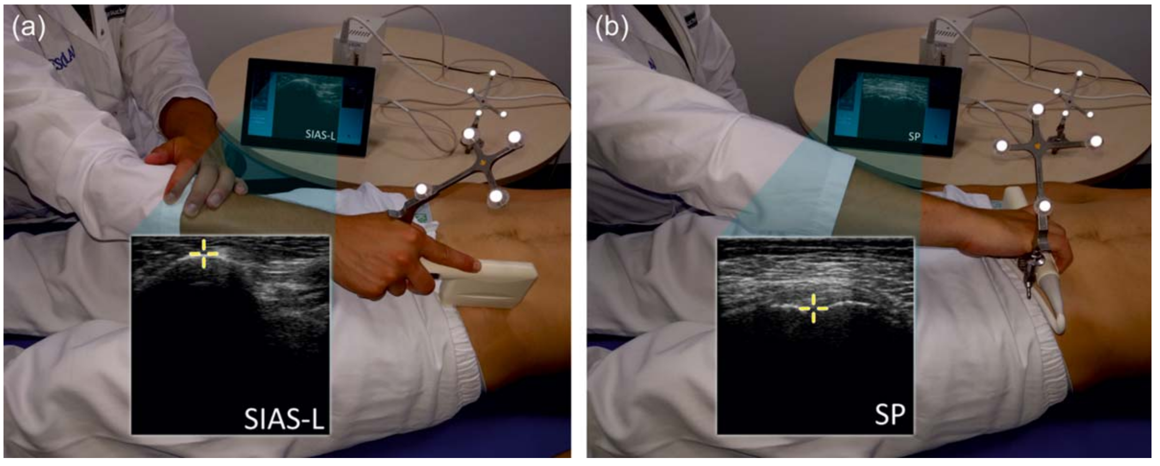
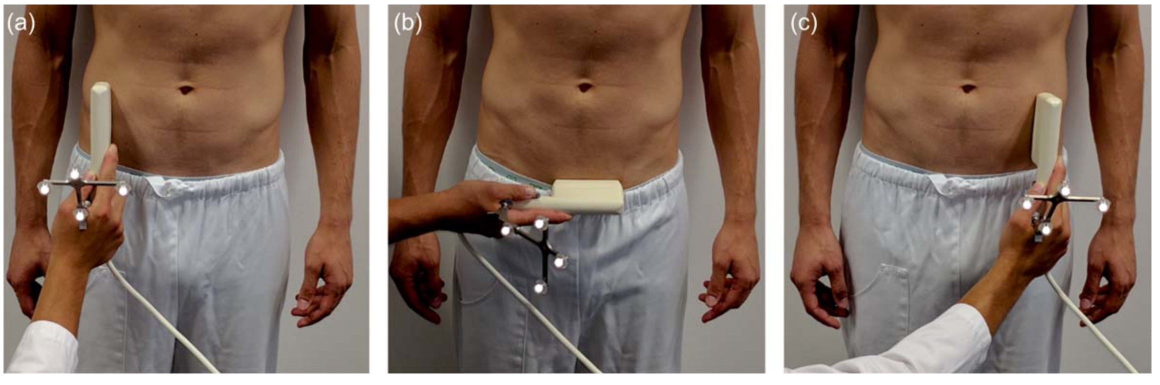



**Figure 6.** Scanning sequence in the standing position: **a**, right anterior superior iliac spine; **b**, pubic symphysis; **c**, left anterior superior iliac spine.



## Results

The results of the measurements are shown in Table 1. According to the convention used by Maratt et al,[13] the values for the pelvic tilt angle are negative for anterior tilt and positive for posterior tilt. In both standing and sitting positions, the angle was measured with respect to the vertical plane. In the supine position the reference plane was horizontal.

## Discussion

The importance of correct placement of the acetabular cup has been emphasized often in various literature, and the position of the patient's pelvis on the operating table has been considered the most obvious factor that affects the final position of the implant. The currently available navigation systems allow introduction of the acetabular component very precisely by intraoperative referencing of its position with respect to the anterior pelvic plane. However, they do not take into account patient-specific changes in the pelvic tilt angle, which may occur when a patient assumes a standing or sitting position. Consequently, although the cup is implanted according to the guidance provided by the navigation system, the load distribution on the acetabular component may be other than intended.

The clinical benefit of using navigation in THR can be improved by making better use of the available measurement methods. One of these methods is navigated US, which proved to be suitable for orthopedic measurements as a noninvasive, accurate, and reliable technique. It has been already applied intraoperatively in commercially available navigation systems, eg, the latest generation of OrthoPilot (Aesculap AG), for THR and knee osteotomy. In this work, this technique was adapted for low-cost measurements in preoperative and postoperative settings. With no preoperative information on the specific anatomy of the patient, current navigation systems assume the anterior pelvic plane to be vertical in the standing position.[8,14] By incorporating the preoperative measurements into the work flow, the cup can be readjusted in a way that the guidelines for implantation will be satisfied for the actual functional position of the patient, rather than for the position on the operating table.

The results of the measurements done in this study were generally consistent with those reported by the

**Table 1.** Results of the Pelvic Tilt Angle Measurements in the Patients Included in the Study

| | | | Pelvic Tilt Angle, ° | | |
|---|---|---|---|---|---|
| **Patient** | **Side** | **Sex** | **Standing** | **Sitting** | **Supine** |
| 1 | Right | Female | −2.0 | −82.8 | −27.2 |
| 2 | Left | Female | −30.3 | −71.2 | 17.0 |
| 3 | Right | Female | −17.6 | −69.0 | 3.9 |
| 4 | Right | Female | −25.7 | −72.5 | 15.8 |
| 5 | Left | Female | −55.3 | −62.2 | −26.0 |
| 6 | Left | Female | 32.2 | −59.9 | 6.9 |
| 7 | Right | Male | 13.4 | −56.3 | −5.8 |
| 8 | Right | Male | 48.8 | −79.6 | −21.6 |
| 9 | Right | Female | −31.3 | −75.0 | −14.1 |
| 10 | Left | Female | −19.0 | −33.1 | 17.0 |
| 11 | Right | Female | −28.3 | ND | −29.0 |
| 12 | Left | Male | −29.6 | −86.1 | −9.6 |
| 13 | Left | Female | −27.0 | ND | 6.7 |
| 14 | Left | Female | −20.1 | −67.5 | −12.3 |
| 15 | Left | Male | −35.2 | −82.4 | −14.4 |
| 16 | Left | Male | −17.9 | −72.0 | 5.8 |
| 17 | Left | Male | −29.6 | ND | 12.0 |
| 18 | Right | Female | −41.9 | ND | −27.9 |
| 19 | Right | Male | −25.8 | ND | −16.8 |
| 20 | Right | Male | −38.2 | ND | −18.3 |
| Mean ± SD | | | −19.0 ± 24.9 | −69.3 ± 13.6 | −6.9 ± 16.2 |

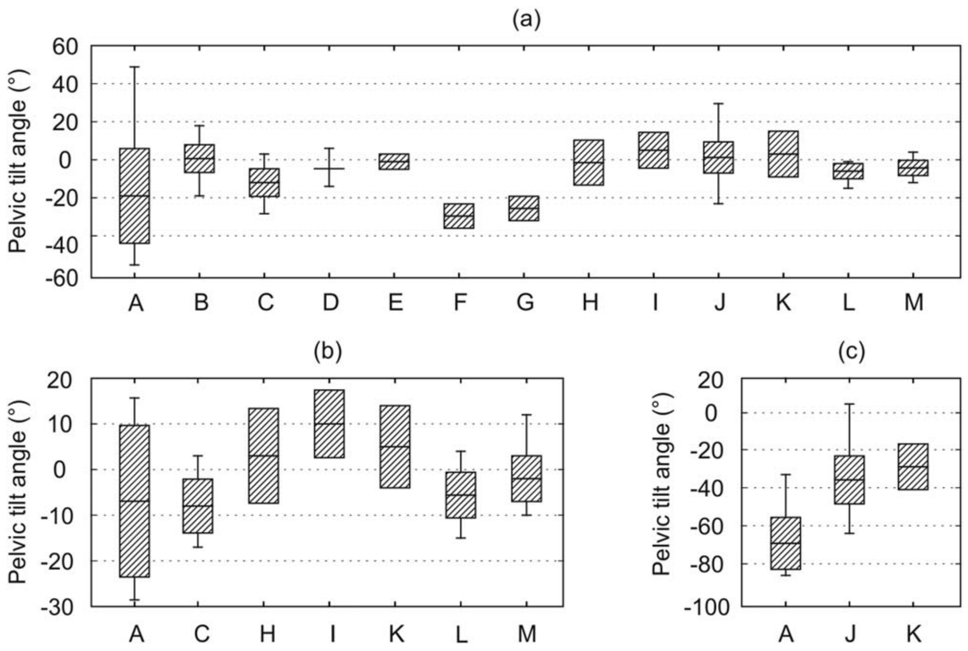
ND indicates no measurements done.

other authors for comparable groups of participants (ie, in patients with osteoarthritis before primary THR) and in similar conditions (preoperatively, in standing, sitting, and supine positions). As can be seen from Figure 7, the mean values for the pelvic tilt angle in the standing and supine positions were in good agreement with the prior research.[13–22] The discrepancy in the mean pelvic tilt angle for the sitting position could be attributed to the difficult access to the pubic bone in overweight patients. It can be also seen that the results obtained in this study are more disperse than those in the other studies, which is reflected by the high standard deviation and large difference between the extreme measured values. A possible explanation for this finding might be that initially, the operators had little experience with the system. This explanation seems especially plausible considering very good repeatability of the measurements observed in previous experiments on phantoms.[11]

In conclusion, in this work, we have presented an original method for measuring the pelvic tilt angle with navigated US and mobile devices. The method was evaluated in a group of 20 patients with hip osteoarthritis for measurements in standing, sitting, and supine positions. The results obtained with the proposed system were comparable to those available in the literature in terms of mean values, but their distribution was substantially wider. Although the wide distribution is an important issue for future research, as it may suggest a need to improve the usability of the system, the main objective of this work was to validate the measurement method. The results obtained here are sufficient to conclude that the method is correct and that it can serve as a basis for future studies.

The possible applications of the presented approach are not confined to preoperative measurements. Considering its mobility and affordability, it may be also used for follow-up examinations of the pelvic tilt after THR or for positioning of the patient on the operating table during preparation for the surgery. Therefore, it is a practical tool that can be easily integrated into the work flow of navigated THR and contribute to more precise, patient-specific positioning of the acetabular component.

**Figure 7.** Comparison of the pelvic tilt values obtained in this work and the results reported by other authors in corresponding groups for standing (**a**), supine (**b**), and sitting (**c**) positions. The middle segments of the hatched boxes show the mean values; the upper and lower edges show the standard deviations; and the whiskers show the minimum and maximum values: A, this work; B, Maratt et al[13]; C, Lembeck et al[15]; D, Blondel et al[14]; E, Legaye[16]; F and G, Watanabe et al[17]; H, Suzuki et al[18]; I, Babisch et al[19]; J, DiGoia et al[20]; K, Nishihara et al[21]; and L and M, Anda et al.[22] In some works,[16–18,21] the minimum and maximum values were not reported. In another work,[14] the standard deviation was not reported.



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