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A Smart Device Based Measuring System for Pelvic Tilt Computation in Hip Arthroplasty

***Abstract**. This article describes a cost-effective, ultrasound-based measuring system for the Pelvic Tilt. The system allows the acquisition of the exact pelvic orientation for each individual patient both pre- and postoperatively. A major advantage of this system is that measurements may be recorded for any patient posture e.g. standing or sitting. Instead, the current state-of-the-art is based on CT or MRI tomography where patients are required to be in a lying position. First experimental results with an artificial hip reference model show very accurate results with maximum deviations of ±1 degree, and ±1.4 degree in different measurement scenarios.*

***Streszczenie.** W pracy opisano niskokosztowy system pomiaru kąta nachylenia płaszczyzny miednicy oparty na urządzeniach mobilnych. System pozwala na pomiar kąta płaszczyzny miednicy dla indywidualnego pacjenta, zarówno przed jak i pooperacyjnie. Główną zaletą opisywanego systemu jest możliwość dokonywania pomiarów dla każdej postawy pacjenta (np. siedzącej lub stojącej) w odróżnieniu od obecnego stanu techniki, gdzie pomiar taki z wykorzystaniem tomografii komputerowej bądź rezonansu magnetycznego może być dokonany jedynie w pozycji leżącej. Pierwsze testy przeprowadzone na sztucznym modelu miednicy dały bardzo dobre wyniki z odchyleniem standardowym wynoszącym ±1 stopień oraz ±1,4 stopnia w innych scenariuszach testowych.(**Pomiarowy płaszczyzny miednicy w artroplastyce stawu biodrowego oparty na urządzeniach mobilnych**)*

Keywords: pelvic tilt, navigated ultrasound, computer assisted surgery, smart devices.
Słowa kluczowe: wychylenie miednicy, nawigowane USG, chirurgia wspomagana komputerowo, urządzenia mobilne

Introduction

Total hip arthroplasty (THA) is a very common surgical procedure in orthopedics and is performed very effectively all over the globe. According to the Federal Office of Statistics more than 210,384 patients received new hip implants during 2013 in Germany alone [1]. Conventional hip arthroplasty requires the skills and experience of the performing surgeon which are based on a subjective and qualitative description of the human anatomy. The requirements for an evidence-based medical approach using valid data is part of the philosophy of computer-aided orthopedic surgery (CAOS). The longevity of the implant relies mostly on the correct alignment of the components. The most critical component is the positioning of the acetabular cup which defines the functional performance of the entire endoprosthesis. The positioning of the acetabular cup is commonly referenced against the anterior pelvic plane (APP) which is defined by distinct anatomical landmarks - these are represented by the left and right spina, and the symphysis pubis [2]. The angle of the plane generated by these landmarks with respect to the coronal plane determines the so-called pelvic tilt (PT) - the orientation can be posterior and anterior. The PT defines a reference for the anteversion and inclination angles which set the basis for a correct alignment of the implants.

In today's navigated hip arthroplasty the measurement of the PT is based on a preoperative image data set which in most cases is acquired in a lying position using computer tomography (CT) or Magnetic Resonance Imaging (MRI). Current state-of-the-art procedures and functional PT positions are based on Lewinnek's angles which define a “safe zone” for a maximum range of motion for an inclination angle of 40±10° and an anteversion angle of 15±10°. Lewinnek's assumptions though are based on measurements in a lying position and only defined for a PT of 0° [3]. Abdel et al. evaluated 9784 primary THAs which had been performed between 2003 and 2012. From 206 (2%) dislocated implants 58% had been placed within Lewinnek's proposed safe zone which led to a big discussion on the relevance and consideration of further requirements [4]. The PT though differs in standing, lying and sitting position depending on various individual parameters. For a conventional THA this fact is not taken into account. Additionally, the main functional pressure on the implant requires its highest performance in a standing position.

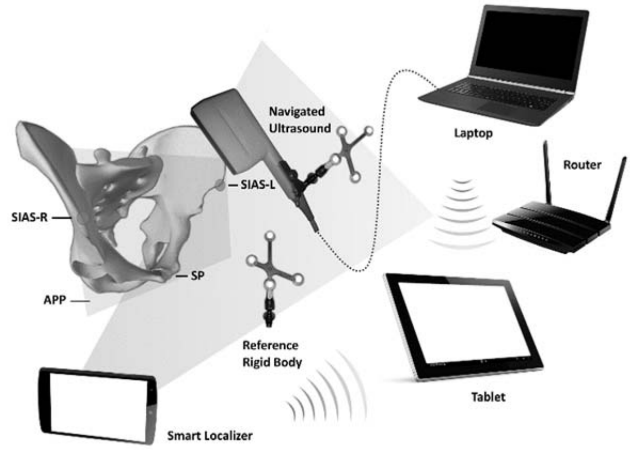

Fig.1. The system consists of the following components: the navigated ultrasound connected to a laptop, a reference rigid body, a smart localizer for calculating the coordinates, a tablet for showing the results and a router for transmission.

In addition the flexibility (range of movement) of the femural head must be guaranteed in all standard conditions e.g. sitting, climbing stairs without the risk of luxation or impingement.

Furthermore, the individual sagittal balance and leg geometry play a major role in the orientation of the hip and it should be evaluated to which extent they influence the PT. For an exact and patient-specific positioning of the acetabular cup a more holistic/integrated acquisition of the anatomic condition of the patient must be considered [5].

For pre- and postoperative acquisition method of patient-customized anatomical angles a measurement system using navigated ultrasound is suggested. Ultrasound provides a cheap, non-invasive and reproducible acquisition of anatomical landmarks without radiation exposure for both the patient and the surgeon. This allows fast pre-, intra- and postoperative, real-time screening in comparison to CT/MRI in various positions.

Material and Methods

To offer a mobile and cost-effective solution the choice fell on smart devices since they had already an all-round hardware equipment. To access the ultrasound image an additional computer is required since there was no possibility for directly linking of the ultrasound device. The system includes the following components (Fig.1): a navigated ultrasonic probe connected to a computer, two passive markers (rigid bodies), a tablet computer, a smart-phone with company-internal tracking software [6] and a wireless router for image and tracking data transmission.

Devices for Measurement

For the measurements a CE-certified ultrasound device (Telemed - Echo Blaster 128) with an attached 9-MHz linear probe and a rigid body (Aesculap) for tracking is used. The rigid body is attached with four spherical markers which are coated with a retroreflective layer and a connector at its bottom. A smartphone is used as a localizer to track the ultrasound probe and a reference marker in real time. The smart-phone localizer works on the principle of imageless navigation. The main software runs on a tablet and communicates with a localizer smartphone and a notebook to receive the ultrasound image. A notebook is used as an interface between the Software.

System Workflow

The reference rigid body is positioned near the patient within the valid measurement volume of the mobile localizer camera. For the determination of the APP this setup is necessary to assign the coordinates of the mobile localizer to a reference point. For the tracking of both rigid bodies a commercially available smartphone is used. The smartphone acts as a mobile system and does not need to be attached to a fixed position. This offers a high degree of flexibility because the position of the localization environment can be changed arbitrarily. Unfavorable measuring positions can thus be easily circumvented for example when the rigid bodies are not in the desired position.

After the start of the application a selection screen appear containing the three anatomical landmarks which define the APP. The order of the selected landmarks may be specified in arbitrary order. After selection, the computer unit is addressed via Wi-Fi and transmits the US-image simultaneously on the tablet. The ultrasound image is transmitted and displayed in real time. As soon as the marker of the rigid bodies are tracked an additional wireless connection between the tablet and the smart localizer. The tablet receives the necessary data which include position and orientation of the ultrasound probe relative to the reference. The surgeon has to find the correct object of interest on the live ultrasound image.The surgeon is notified by an indicator bar on the tablet screen which indicates the current value stability. This is to provide the operator a visual aid before saving the position. After saving the position the ultrasound image is frozen on the screen and a cross marker is displayed. This cross marker is now placed by the surgeon on the anatomical landmark in the ultrasound image. Ideally, the highest point on the contour of the left and right spina iliaca anterior superior is selected. For the symphysis pubis, the transducer is placed longitudinal over the pubic prominence. The right and left pubic bodies are seen as bright hypoechoic curved structures. The pubic symphysis is seen as a darker hypoechoic line between the two bodies. If all three landmarks are acquired the anterior pelvic plane is created. The pelvic tilt is determined as the angle between the APP and the coronal plane. In addition, the application calculates the pelvic balance which describes the tilt of the patient pelvis around the sagittal axis. For further use the pictures, coordinates and angles are saved on the smart device.

Referencing of the Ultrasonic Probe

The aim is to correlate the 2D image obtained with the navigated ultrasound probe with the coordinates of smart device localizer. The coordinate system of the rigid body which is mounted on the ultrasonic probe has its absolute zero on the connector which combines these two components.

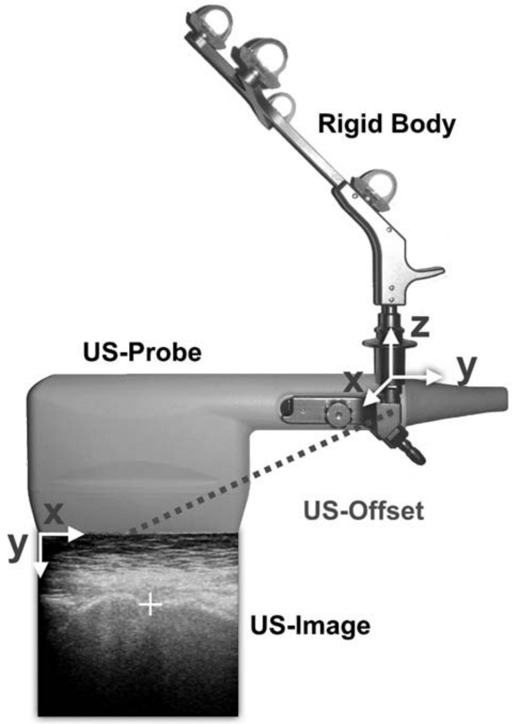

Fig.2. Representation of the calculated offset of the ultrasound probe (dotted line) and 2D US-image. The coordinate systems of the components are adapted to the rigid body coordinate system.

The smart localizer makes it possible to calculate the 3 ×3 rotation (R) and translation (t) matrices of the rigid body in camera coordinates (formula 1).

$$T_{RB} = \begin{bmatrix} R_{11} & R_{12} & R_{13} & tx \\ R_{21} & R_{22} & R_{23} & ty \\ R_{31} & R_{32} & R_{33} & tz \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

To combine the ultrasound image with the obtained coordinate data an additional matrix which forms the center of the scan US transducer head is multiplied as an offset (formula 2) to the rigid body matrix (formula 3). T_{Offset} consists of an identity matrix and an offset [7].

$$T_{Offset} = \begin{bmatrix} 1 & 0 & 0 & x_{Offset} \\ 0 & 1 & 0 & y_{Offset} \\ 0 & 0 & 1 & z_{Offset} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$T_{Probe} = T_{RB} \cdot T_{Offset} \quad (3)$$

In order to set the absolute zero point to the point selected by the surgeon on the ultrasound image

($T_{US-Image}$) the image must be converted to millimeters by its pixel size and scan depth.

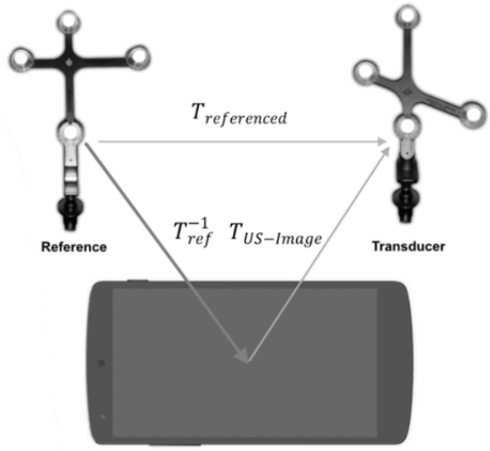

Fig.3. Transformation of the ultrasound rigid body is calculated from camera coordinate system to reference coordinate system.

The pixel dimensions of the ultrasound image which is displayed on the tablet are uniform in height and width. By the known dimensions of the transducer and the scanning depth currently used the selected anatomical landmark can be represented in the camera coordinate system. As described in the formula 3 this value is additionally added up as an offset.

(4) $$x_{Picture} = \frac{Transducer_{Width}\ [mm]}{Picture_{Width}\ [px]}$$

(5) $$y_{Picture} = \frac{Transducer_{Depth}\ [mm]}{Picture_{Height}\ [px]}$$

Due to the fact that the smartphone tracks the rigid bodies in a non-static position and hence is constantly moves, and furthermore the single markers have no relationship to each other they must be referenced. For referencing with respect to the rigid body coordinate system the rotation matrix of the reference has to be inverted and then multiplied with the rotation matrix of the recorded position of the ultrasound probe.

(6) $$T_{referenced} = T_{ref}^{-1} \cdot T_{US-Image}$$

Calculation of the Pelvic Tilt

Clamping of APP (see Fig. 4) by calculating the vectors $\vec{a}$ and $\vec{b}$, with the two landmarks SIAS-L and SIAS-R depending on the landmark SP. By calculating the cross product of vectors $\vec{a}$ and $\vec{b}$, we obtain the normal vector $\vec{c}$ to the APP.

(7) $$\vec{c} = \vec{a} \times \vec{b} = \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} \times \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix}$$

where:

$$\vec{a} = \overrightarrow{SIASL} - \overrightarrow{SP}$$

$$\vec{b} = \overrightarrow{SIASR} - \overrightarrow{SP}$$

To determine the PT the ground defined vector $\vec{z}$ and the normal vector $\vec{c}$ is required. Vector $\vec{z}$ is defined here over the reference rigid body. The angle $\tilde{\beta}$ is calculated from the dot product of these two vectors. Angle $\tilde{\alpha}_{PT}$ in this case represents the PT.

(8) $$\tilde{\beta} = arccos\ \frac{\vec{c} \cdot \vec{z}}{|\vec{c}| \cdot |\vec{z}|}$$

Where:

$$\tilde{\alpha}_{PT} = 90° - \tilde{\beta}$$

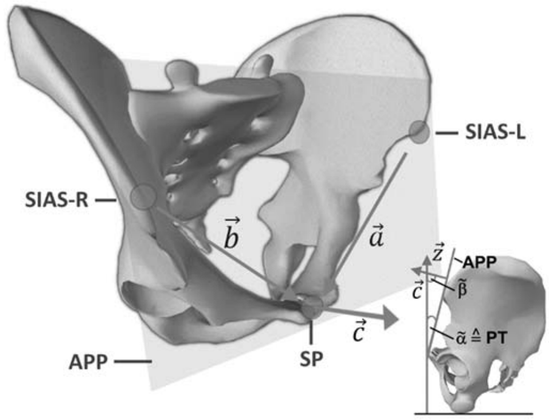

Fig.4. The anterior pelvic plane (APP) is defined by three bony landmarks which draw a plane which in turn serves as a reference for the so-called pelvic tilt (PT). The APP is defined by the left and right most anteriorly prominent aspect of the spina iliaca anterior superior (SIAS-L, SIAS-R) and the most prominent, anterior portion of the symphysis pubica (SP).

Results

To examine the accuracy and reproducibility of the software and PT measuring system, ten measurements were performed with two different variations [8]. For the evaluation and feasibility a hip phantom was used (Fig.5), which was adjusted at a posterior angle of 20 degrees. The hip phantom was measured in two different variations with the smartphone localizer. The smartphone was first fixed at a position and in the second measurement, it was held by hand. A calibrated inclinometer was used to verify the position set.

Table 1. Results of two measurements for a PT of 20° posterior

PT: 20° posterior Smartphone: Fixed		*PT: 20° posterior Smartphone: Mobile*	
Measurement	*Nexus*	*Measurement*	*Nexus*
1	**19,8°**	*1*	**21,4°**
2	**20,2°**	*2*	**20,6°**
3	**20,9°**	*3*	**21,4°**
4	**19,5°**	*4*	**19,6°**
5	**20,4°**	*5*	**20,1°**
6	**21,0°**	*6*	**20,7°**
7	**19,9°**	*7*	**20,1°**
8	**19,5°**	*8*	**20,3°**
9	**20,3°**	*9*	**21,3°**
10	**20,8°**	*10*	**19,8°**
Average	**20,2°**	*Average*	**20,5°**
Standard Deviation	**± 0,6°**	*Standard Deviation*	**± 0,7°**

Fig.5. For the accuracy of the measurements a hip Phantom, composed of the three desired landmarks, was used and checked with the protractor Tesa Clino Bevel 1.

The accuracy tests of a preset pelvic tilt show a maximum deviation raging between ±1 degrees for a fixed position of the localizer and ±1.4 degrees in mobile use. The values of both measurements show very similar results. The fixed position thereby has a slight advantage, because their values (in case of Standard Deviation) scatter a little less than the mobile version. In carrying out the measurements several alleged errors could occur.

Possible Sources of Errors

After a landmark was chosen on the ultrasound image the surgeon shouldn't make divergent motions during the acquisition of the localizer data. A blurred recording of the ultrasonic probe can lead to a wrong calculated offset/rotation of the probe and the ultrasound image. It is essentially important that the surgeon indicates the landmarks correctly and that his selection point is placed exactly on the US-image (Fig.2). If the localizer is used it is important that the acquisition is virtually motionless performed as fast movements during the acquisition of the markers may also lead to a distortion of the values. For the scenario of measuring a patient it must also be noted that he is not allowed to move. Throughout the acquisition of the landmarks the patient's position needs to be maintained in order to avoid further error influences. This can be achieved by fixation of the patient with a suitable device. For a standing patient, the fixation could be combined in the form of a vertical surface.

Conclusion

An easy-to-use measuring prototype application for navigated ultrasound has been developed. This system meets all minimally-invasive surgery needs, in use and calculation of the pelvic tilt. The results look promising with respect to the accuracy of the application. With this measuring system, it's in addition to the conventional method possible to measure patients in a standing and sitting position. The whole measurement works with no radiation exposure at all which is highly important for patients. For further action and the possible clinical use the system should be assessed regarding its usability on the basis of in-vitro studies.

This development should also show how smart devices can be integrated in terms of their hardware technology components in the medical field to provide a quick and cost-effective application of case-specific solutions for the medical staff. The digital world forms itself more and more in terms of smart devices. These devices accompany us in our everyday environment and possess many useful components which provide medical benefits. This boom causes a steady growth of operating systems and their innovations and improvements regarding both software and hardware side.

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