Development and assessment of a Microsoft Kinect based system for imaging the breast in three dimensions

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Development and assessment of a Microsoft Kinect based system for imaging the breast in three dimensions

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Abstract

Three-dimensional surface imaging technologies have been used in the planning and evaluation of breast reconstructive and cosmetic surgery. The aim of this study was to develop a 3D surface imaging system based on the Microsoft Kinect and assess the accuracy and repeatability with which the system could image the breast. A system comprising two Kinects, calibrated to provide a complete 3D image of the mannequin was developed. Digital measurements of Euclidean and surface distances between landmarks showed acceptable agreement with manual measurements. The mean differences for Euclidean and surface distances were 1.9 mm and 2.2 mm, respectively. The system also demonstrated good intra- and inter-rater reliability (ICCs $>$ 0.999). The Kinect-based 3D surface imaging system offers a low-cost, readily accessible alternative to more expensive, commercially available systems, which have had limited clinical use.

Keywords: three-dimensional scanning, mammometrics, agreement, mannequin, breast surgery

1. Introduction

Three-dimensional (3D) surface imaging technologies are used in several health and medical domains. For example, in cephalometrics measurements taken from planes and points – generated from facial anatomical landmarks – are used to plan and evaluate surgery [1, 2]. Recently, Tepper et al. [3] introduced mammometrics in which objective breast measurements are taken from planes and points established based on torso anatomical landmarks [3]. Reconstructive and aesthetic clinical applications of mammometrics through 3D surface imaging have been explored. For example, Liu et al. [4] evaluated the use of 3D surface imaging in the assessment of breast asymmetry before breast augmentation. They demonstrated high incidence of asymmetry and suggested that 3D surface imaging techniques are important in the selection of optimal implants [4]. Tepper et al.

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[3] explored the use of 3D images in aiding breast reconstruction. They suggested that 3D surface imaging can be used effectively at various stages of breast reconstruction [3].

The validity of 3D surface imaging techniques in obtaining mammometric measurements has also been investigated [5, 6]. Losken et al. [5] investigated the accuracy with which 3D surface distances, for example, could be estimated. The mean difference between manual – taken with a tape measure – and 3D digital distances was approximately 6%. More recently, Catherwood et al. [6] demonstrated that a commercially available surface imaging system could be used to obtain accurate measurements of the breast. By imaging a female mannequin of known dimensions, Catherwood et al. [6] reported good agreement between manual – taken with Vernier Callipers – and 3D image based estimates of the Euclidean distances between anatomical landmarks (mean difference: 0.88 mm). Further, they demonstrated good agreement for important mammometric surface distances (mean difference: 1.36 mm) and mammometric plane-to-anatomical point distances (mean difference: 1.94 mm).

In summary, 3D surface imaging systems have been used to obtain measurements of the breast and their potential benefits have been highlighted. Further, 3D surface imaging systems have been demonstrated to be accurate and reliable in estimating mammometric parameters. However, in clinical practice, the use of 3D surface imaging is limited and manual tape-/calliper-based measurement predominates [7]. Possible reasons for this include the perception that 3D surface imaging techniques are complex and require a highly skilled user [3]. Also, 3D surface imaging systems are generally expensive - commercially available systems cost in the order of $10,000 to $60,000 [3].

Recently, Microsoft released the Kinect – a peripheral device for the Xbox360 and Windows. This revolutionary device has received much attention from the academic community in many disciplines including, health, robotics, biomechanics and engineering. Although the Kinect has several technological features, the majority of interest has focussed on its 3D depth camera. Using a pseudo- structured light scanning approach, the Kinect returns the distance between it and objects in the field-of-view, enabling the generation of a 3D model. Many applications are possible and several recent investigations have explored the accuracy of the Kinect in various contexts. For example, Clark et al. [8] investigated the accuracy with which joint kinematics could be estimated from the depth data. They reported that the Kinect generates data comparable to that provided by complex and expensive 3D motion capture systems [8]. Studies have also explored the use of the Kinect for 3D surface imaging [**?**], drastically reducing the cost of the 3D surface imaging system

- a Kinect costs approximately $300. The Kinect and other commodity depth cameras offer the potential to perform 3D surface imaging-based mammometric analyses for a fraction of the cost of currently available commercial systems.

Oliveira et al. [**?**] recently highlighted that a Kinect-based 3D surface imaging system can be used to obtain accurate measurements of the breast. However, a comprehensive analysis of the accuracy and reliability of the system was not provided and only one inter-anatomical landmark distance was considered. Therefore, our aim was to develop a 3D surface imaging system based on the Kinect and - using an approach similar to Catherwood et al. [6] - assess the accuracy and repeatability with which the system could image a female mannequin in 3D. Specifically, we compared Euclidean and surface distances calculated with the Kinect-based surface imaging system to manual tape-/calliper-based measurements.

2. Methods

2.1. The Kinect-based 3D surface imaging system

Three-dimensional images were obtained using a Kinect-based surface imaging system which comprised two Kinects, two tripods and a basic consumer laptop PC (Dell Vostro, Intel ® Core™ 2 Duo , 2.2 GHz, 3 GB RAM). The Kinects were placed on the tripods with their optical axes separated by an angle of approximately 70 ° - with the test object in the field-of-view, approximately 700 mm away from each Kinect (Figure 1). During development, our aim was to keep the system as simple as possible. Using only one Kinect would have been less complex. However, initial tests indicated that a minimum of two Kinects were required to produce a complete point cloud of our test object - the lateral and anterior aspects of the mannequin. The custom written software for the system uses the freely available *Kinect for Windows* (Microsoft, Redmond, WA, USA) Software Development Kit (SDK) to obtain depth maps, from which three-dimensional point clouds of the scene are created using a camera model. The Kinect's depth and colour cameras have a resolution of 640 x 480 pixels and the combined 3D images of our test object produced point clouds comprising approximately 160,000 points. No calibration of the intrinsic parameters of the Kinects was required as a function in the *Kinect for Windows* SDK is used which accesses parameters stored in each Kinect's non-volatile memory.

Two 3D point clouds of the scene are produced – one from each Kinect – which required transformation (rotation and translation) to produce a complete scan. Several approaches to defining this transformation have been presented, including those based on three, or more, spheres in the scene or iterative closest point algorithms used with complex calibration objects or based on features of the object being scanned [**?**].We used a simple and quick approach which requires a planar object containing a checkerboard pattern to be placed in approximately the centre of the field-of-view of both Kinects (held stationary by leaning the board on a prop placed behind it). Single images from each Kinect's rgb and depth cameras of the static planar checkerboard are needed. The coordinates of the intersections of the checkerboard pattern were extracted in the image plane of the rgb camera using EMGU (www.emgu.com). Functions in the *Kinect for Windows* SDK were then used to transform points in the rgb image plane into depth camera image coordinates before transformation into the 3D coordinate system of the Kinect using the depth data from, and the intrinsic parameters of, the depth camera. Parenthetically, because of the interference caused by the overlapping pseudo-structured infra-red light projected by multiple Kinects, data from each device were obtained sequentially, ensuring the infrared projector of only one Kinect was operational at any time. The infra-red projectors were controlled through software.

Given the two sets of N (in the current study we used a pattern of 11 by 8 squares, producing 70 points) corresponding 3D points (p) in each Kinect's 3D coordinate system (Kinect 1: p_1, Kinect 2: p_2), the 3x3 rotation matrix (R) and 3x1 translation vector (v) components of the transformation between them were obtained using a common approach based on singular value decomposition [9]. First, the mean location of the points in each Kinect's 3D coordinate system were subtracted from the point locations, decoupling rotation and translation. The rotation was estimated by, first, generating a matrix, A:

$$A = \bar{p}_1(\bar{p}_2)^T \tag{1}$$

where $\bar{p}_1$ and $\bar{p}_2$ are 3 x N matrices containing the coordinates, with the mean position subtracted, of the corresponding three-dimensional points in the coordinate system of Kinect 1 and Kinect 2, respectively. Subsequently, the singular value decomposition of A was calculated such that:

$$UDV^T = A \tag{2}$$

R was then obtained as

$$R = VU^T \tag{3}$$

Once the rotation component of the transformation was known, the translation could be obtained using:

$$v = m_2 - Rm_1 \tag{4}$$

where m_1 and m_2 were the mean locations of the corresponding points in the coordinate system of Kinect 1 and Kinect 2, respectively.

Obtaining three dimensional scans with the Kinect-based system involved a similar process to calibrating the system. With the object to be scanned in the field-of-view of both devices, data from the rgb and depth cameras were obtained sequentially from both Kinects - with the infra-red projector of the non-active Kinect disabled, eliminating interference. The total duration of the scan was approximately two seconds - during this time data from both Kinects were collected. Three-dimensional point clouds were created from each Kinect using the depth data and the intrinsic parameters of the depth camera, with colour from the rgb camera projected onto the points in the point cloud, generating a coloured model. The transformation parameters (R and v) were then applied to align the scans from the two Kinects, producing the final point cloud model.

2.2. Agreement with manual measurement

A female mannequin – of similar dimensions to that used by Catherwood et al. [6] – was scanned with the Kinect-based system (Figure 2). Markings on 17 anatomical landmarks (Table 1) were added to the mannequin using white circular labels (diameter 13 mm) with a pen marking at their centre (diameter 3 mm). The location of the anatomical markings were confirmed by a specialist oncoplastic breast surgeon (AG). The mannequin was positioned approximately 700 mm from the Kinects (Figure 1). The 17 anatomical landmarks were manually identified in a three-dimensional view of the point cloud models obtained using our surface imaging system. We replicated several relevant experiments performed by Catherwood et al. [6] to investigate repeatability of the Kinect-based surface imaging system and agreement with manual measurements.

First, straight line Euclidean distances between pairs of anatomical landmarks – similar to those estimated by Catherwood et al. [6] – were calculated and compared to manual measurements of the distances – taken using Vernier callipers. The mean of three repeated manual measurements was recorded. Three repeated analyses of one scan of the mannequin were performed, producing mean measurements of distance with the Kinect-based system.

We also measured the surface distance (d) between two points (A and B) on the mannequin (Figure 3) as these are also important in mammometric analyses [3]. Given a continuous surface ($\mathbf{S}$), a direction vector ($\mathbf{v}$) and a plane ($\mathbf{P}$) with the normal $\mathbf{v} \times \overrightarrow{AB}$, d is the shortest continuous curve on S between A and B and contained within $\mathbf{P}$. The system approximates $\mathbf{S}$ as a series of discrete points $p_{1\dots n}$. To describe a continuous curve, points between A and B and within 1 mm of $\mathbf{P}$ were fit with a smoothing spline to give d. Surface distance was minimised by searching possible values for $\mathbf{v}$. An initial plane was formed from $\overrightarrow{AB}$ and a normal vector $\mathbf{v}_n$ – calculated using point cloud data and algorithms from the point cloud library (pointclouds.org) – at either point A or B, depending on which yielded the lower initial d value. An optimisation routine (a matlab based gradient descent method) was used to modify $\mathbf{v}_n$ by rotating it about $\overrightarrow{AB}$ until d was minimised.

To enable comparison with previously published data using a commercially available 3D surface imaging system, agreement between manual and Kinect-based system measurements was assessed using the approach of Catherwood et al. [6]. Agreement was assessed by calculating the mean and percentage difference between the manual and Kinect-based system measurements [6]. Intra-rater repeatability was assessed by performing a repeat collection with the system - approximately 20 minutes after the first - and repeating the analysis. The system was dismantled, re-assembled and re-calibrated before the repeat data were obtained so the intra-rater repeatability includes an element related to system set-up. Inter-rater reliability was assessed by asking a second rater - blinded to the analysis of the first rater - to repeat the distance measurements on one 3D image (the first). In both the intra- and inter-rater analysis, the mean of three measurements was recorded. Similar to Catherwood, repeatability was assess using the intra-class correlation coefficient (ICC, ICC(2,1)[**?**]). The ICCs were supplemented with limits of agreement analysis [10].

3. Results

Measurements of Euclidean distances between anatomical landmarks with the Kinect-based system showed acceptable agreement with the manual measurements (Table 2). The mean difference was 1.9 mm (1.2%) – maximum 4.9 mm (4.1%) and minimum 0.1 mm (0.0%). ICCs for intra- and inter-rater repeatability were very high (intra-rater ICC $>$ 0.999 and inter-rater ICC $>$ 0.999). The ICC analyses were supplemented with limits of agreement analysis. Bland-Altman plots are provided in Figure 4 and Figure 5. Mammometric surface distances showed marginally worse agreement with manual measurement (Table 3), with a mean difference of 2.2 mm (1.6%) - maximum 3.4 mm (3.7 %) and minimum 0.1 mm (0.1%).

4. Discussion

The Microsoft Kinect offers the potential for low-cost, readily accessible surface imaging systems, capable of imaging the breast in three dimensions. The aim of this work was to develop a 3D surface imaging system based on the Kinect. A further aim was to compare distance measurements taken with the system with manual tape-/calliper-based measurements. The Kinect-based system showed acceptable agreement with the manual measurements. The accuracy and repeatability of other, commercially available, 3D surface imaging systems in assessing breast morphology have been investigated. For example, Losken et al. [5] reported differences of approximately 6% between manual (tape) and digital estimates of the surface distance between the sternal notch and the nipple. The difference of 1.7% presented in the current study for the same distance compares favourably. However, Losken et al. [5] performed their analysis on human participants, possibly introducing other causes of differences e.g. soft tissue depression.

Agreement between the digital and manual measurements in the current study is worse than that presented by Catherwood et al. [6]. Catherwood et al. [6] imaged a mannequin - similar size to that used in the present study, with the same anatomical landmarks - using a relatively expensive, commercially available 3D surface imaging system. Mean differences in Euclidean and surface distance of 0.88 mm and 1.36 mm, respectively, were reported. However, we believe that agreement between the Kinect-based system and manual measurements should still be considered acceptable - certainly when the simplicity, accessibility and cost of the Kinect-based system is considered. Like Catherwood et al. [6] - who suggested that a mean difference of 0.88 mm is not clinically significant - we would not expect mean differences between manual and digital measurements of distance of 1.9 mm and 2.2 mm to be clinically significant in breast surgery. However, further work is required to establish clinical consensus on what is acceptable accuracy for three-dimensional imaging of the breast. This will allow the usefulness of the Kinect-based scanning system for different applications to be judged.

Like other three-dimensional surface imaging systems, the Kinect-based system has several benefits over traditional tape/calliper measurements. For example, the time taken to obtain mammometric measurements is reduced. Each scan takes approximately two seconds to complete. This has the potential to reduce time requirements for the patient, healthcare staff and the surgeon. Indeed, there is potentially no requirement for the surgeon to be present at the scan; measurements can be taken on the 3D point cloud outside of clinic. Three-dimensional scans can also provide an objective record of the breast, facilitating the planning and evaluation of breast surgery. For example, recently, Quan et al. [11] demonstrated how 3D surface imaging can be used to objectively monitor breast morphology following short-scar medial pedicle breast reduction surgery.

Another benefit of 3D surface imaging is that measurements can be taken that are not possible or difficult to obtain using manual tape-/calliper-based methods. Tepper et al. [3] defined a mammometrics framework, suggesting a standardised set of anatomical points, planes, distances and volumes. Many of these parameters cannot be defined through manual measurement. In assessing the Kinect-based system, we considered only the subset of mammometric parameters for which we could obtain manual measurements for comparison. Future work should explore the use of the Kinect-based system for obtaining additional mammometric parameters such as breast volume and the distance between points and mammometric planes. Work could also focus on the automation of mammometric parameter measurements, with algorithms to, for example, automatically detect the centre of markings on the skin.

Our aim during development of the system was to keep the solution as simple as possible. Initial investigations confirmed that one Kinect was not sufficient to capture the full surface of the mannequin and all anatomical landmarks. Two Kinects were sufficient for this purpose but the rigid transformation between them needed to be estimated via a calibration procedure. Several approaches to calibration were possible but we chose to adopt an approach based on a planar, checkerboard calibration object. This method is simple and quick - set-up and collection of the calibration takes less than one minute. Other approaches, similar to that presented by Posada et al. [**?**], offer the possibility of removing the requirement for a stand-alone calibration, potentially improving the flexibility of the system. Using features of the the object being scanned - with enough surface common to each Kinect - individual point clouds can be registered to produce a complete scan. Future work should explore the application of other approaches to estimating the transformation between the Kinects in the context of breast surface imaging. Regardless of the approach used for calibration/registration, transformation between Kinects introduces a source of error that is not present with only one device. Agreement between manual and digital measurements of distance could be improved by including a third Kinect, placed directly in front of the mannequin, from which most (approximately 70%) of the measurements could be taken in isolation. Only for measurements for which one Kinect does not suffice – such as, for example, those involving the lateral aspect of the inframammary fold – would data from the other two Kinects be used. There would be an increased complexity of the system but this would be minimal and the inclusion of a third Kinect should be explored. Indeed, a third Kinect might be required anyway to capture greater complexity when the system is used to image human breasts. Large ptotic breasts can be problematic for 3D surface imaging systems as they can prevent the capture of the lower pole and inframammary fold [12]. Placing a third Kinect lower, with an upward viewing angle would help address these issues [12, 13].

In addition to the greater complexity of the breast surface, there would be other issues when using the Kinect-based system to scan human breast rather than the mannequin used in this study. Movement of participants during the scan - due to breathing and changes in position - is problematic when images from multiple cameras are combined. The duration of the scan with the Kinect-based system presented in this paper is approximately two seconds - during which time data from each Kinect are obtained sequentially. This duration is similar to commercially available three-dimensional imaging systems used in previous mammometric studies [12, 14, 15] which Tepper et al. [12] reported to take approximately two seconds to capture the entire scan area. When the system is used to image human breasts, protocols used in previous studies could be used to reduce participant movement during the scan - with participants having their backs supported by a wall and holding their breath, for example [15]. Additionally, further development/optimisation of the Kinect-based scanning system could reduce the scan duration. Furthermore, point cloud registration techniques (such as that presented by Posada et al. [**?**]) could help reduce the effects of small movements of the participant. However, further work is required to ascertain how robust these techniques would be to changes in the shape of the torso and breast due to breathing.

Distances estimated using the Kinect-based system were compared to manual measurement. There are some limitations of this approach. First, there might be inaccuracies associated with the manual measurement equipment, especially the material tape measure used for the surface distance. Second, for the surface distances, the path defined between two anatomical points could have been different between the manual and digital techniques. The objective function of the optimisation used for the digital data ensured, objectively, that the shortest distance between landmarks was chosen. Ensuring this is the case for manual measurements is difficult. Further, there are obvious practical problems with using a tape to measure curved surface distances. Nevertheless, using manual measurements of distance provided a comparison with what is currently accepted clinical practice [7].

In summary, we have developed a surface imaging system based on Microsoft Kinect capable of imaging the breast in three-dimensions. The system is simple and low-cost, addressing some of the limitations associated with current 3D surface imaging implementations that have limited their more widespread use [3]. By implementing an assessment procedure similar to that used by Catherwood et al. [6] we have demonstrated that measurements of Euclidean and surface distances taken with the Kinect-based system show acceptable agreement with manual measurements. Future work should explore the use of the system for taking measurements on human participants. The calculation of other mammometric parameters, such as breast volume, should also be explored.

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Table 1: Anatomical landmarks on the mannequin (adapted from Catherwood et al. [6])

1, 2	Acromial extremity of the clavicle
3	Suprasternal notch
4, 5	Anterior axillary fold
6, 7	Nipple
8, 11	Lateral point of the inframammary fold
9, 10	Medial point of the inframammary fold
12, 13	Inferior point of the inframammary fold
14	Xiphoid process
15	Umbillicous
16,17	Anterior superior illiac spine

Table 2: Agreement between mean (n = 3) straight line Euclidean distances taken using Vernier callipers and the Kinect-based three-dimensional surface imaging software

Landmarks	Manual (mm)	3D scanner (mm)	Difference (mm)	Percentage Difference
1-3	124.6	119.7	4.9	3.9
2-3	117.7	118.0	0.3	0.2
4-5	256.3	257.1	0.9	0.3
6-7	159.4	160.9	1.5	0.9
8-9	131.7	132.9	1.3	1.0
10-11	132.3	132.1	0.2	0.1
3-6	170.1	172.3	2.3	1.3
3-7	171.4	175.6	4.3	2.5
6-12	78.3	77.3	1.0	1.2
7-13	79.7	76.4	3.3	4.1
3-14	233.8	238.1	4.3	1.9
16-17	197.1	197.9	0.9	0.4
8-16	248.3	249.2	0.8	0.3
11-17	247.9	248.8	0.9	0.4
6-15	225.7	228.4	2.7	1.2
7-15	226.0	227.1	1.1	0.5
12-17	268.7	268.7	0.1	0.0
13-16	262.1	265.2	3.1	1.2

Table 3: Agreement between mean (n = 3) mammometric straight line Euclidean and surface distances taken using measuring tape, Vernier callipers and the Kinect-based three-dimensional surface imaging software

	Measurement		Landmarks	Manual (mm)	3D scanner (mm)	Difference (mm)	Percentage Difference
Euclidean distance	Sternal-notch-nipple	Right	3-6	170.6	172.3	2.3	1.3
		Left	3-7	171.4	175.6	4.3	2.5
	Nipple-inferior	Right	6-12	78.3	77.3	1.0	1.2
		Left	7-13	79.7	76.4	3.3	4.1
	Lateral-medial	Right	8-9	131.7	132.9	1.3	1.0
		Left	10-11	132.3	132.1	0.2	0.1
Surface distance	Sternal-notch-nipple	Right	3-6	171	173.3	2.3	1.3
		Left	3-7	173	176.4	3.4	2.0
	Nipple-inferior	Right	6-12	80	80.1	0.1	0.1
		Left	7-13	81	78.0	3.0	3.7
	Lateral-medial	Right	8-9	170	172.9	2.9	1.7
		Left	10-11	173	174.7	1.7	1.0

Figure 1: The system setup. a) the approximate location of the Kinects relative to the mannequin, b) a Kinect with a representation of the infrared (IR) projector, IR camera and red, green, blue (rgb) camera and c) the checkboard pattern used for calibration.

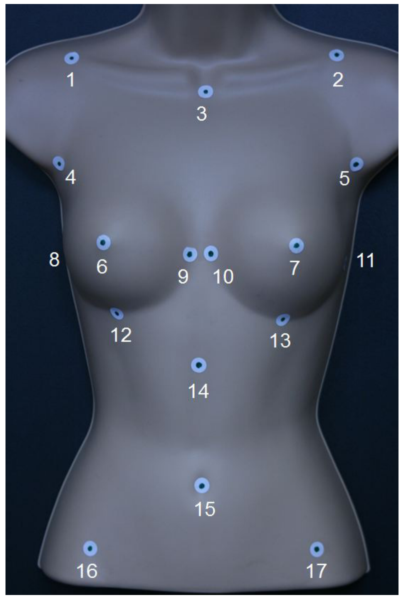

Figure 2: The female mannequin showing the surface landmarks 1-17

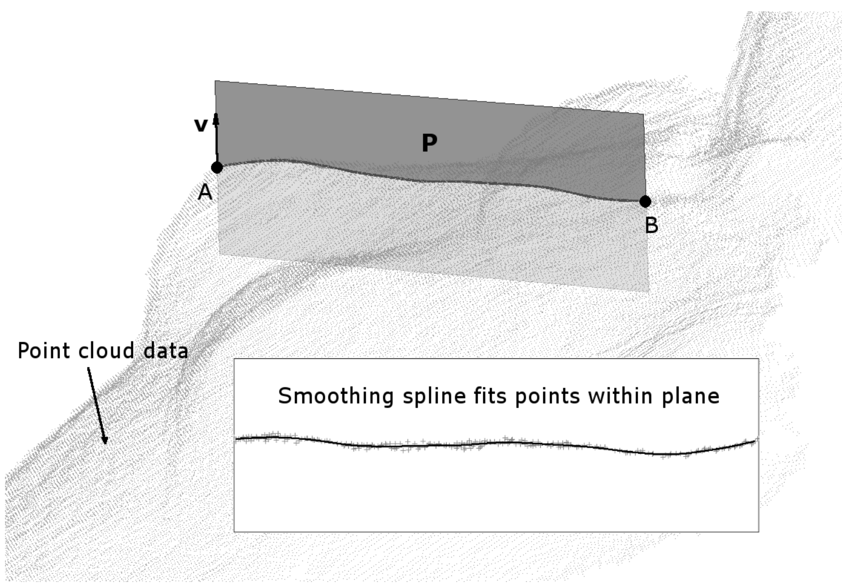

Figure 3: The surface distance is the shortest continuous curve on the point cloud between A and B and contained within $\mathbf{P}$. Shown is the distance between the sternal notch and right nipple. See text for more details

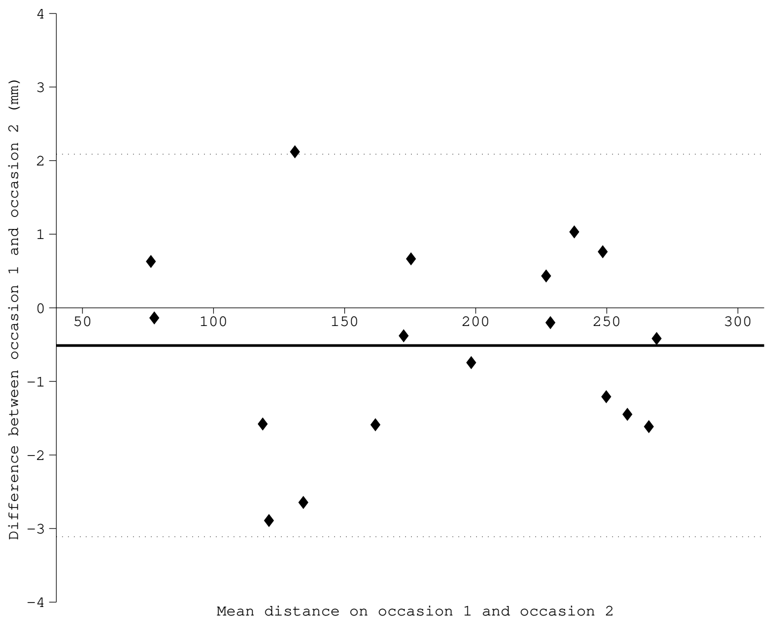

Figure 4: Intra-rater repeatability for 3D Euclidean distance measurements. The sold line is the systematic difference (mean difference) between manual and digital measurements and the dotted lines are the limits of agreement (mean difference ± 1.96*standard deviation of the differences)

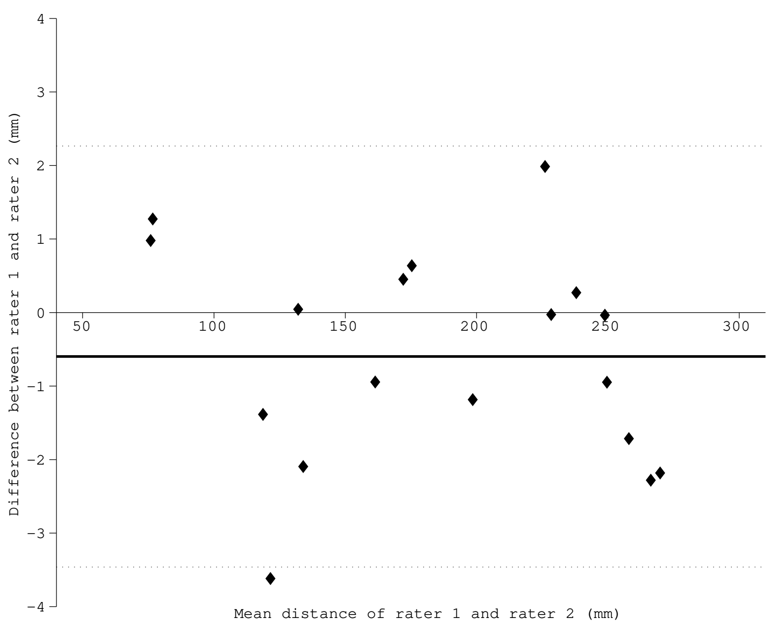

Figure 5: Inter-rater repeatability for 3D Euclidean distance measurements. The sold line is the systematic difference (mean difference) between manual and digital measurements and the dotted lines are the limits of agreement (mean difference ± 1.96*standard deviation of the differences)