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

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6 **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.

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

8 **1. Introduction**

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

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18 [3] explored the use of 3D images in aiding breast reconstruction. They suggested that 3D surface
19 imaging can be used effectively at various stages of breast reconstruction [3].

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

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

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

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

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

60 **2. Methods**

61 *2.1. The Kinect-based 3D surface imaging system*

62 Three-dimensional images were obtained using a Kinect-based surface imaging system which
63 comprised two Kinects, two tripods and a basic consumer laptop PC (Dell Vostro, Intel[®] Core[™]
64 2 Duo , 2.2 GHz, 3 GB RAM). The Kinects were placed on the tripods with their optical axes
65 separated by an angle of approximately 70° - with the test object in the field-of-view, approximately
66 700 mm away from each Kinect (Figure 1). During development, our aim was to keep the system
67 as simple as possible. Using only one Kinect would have been less complex. However, initial tests
68 indicated that a minimum of two Kinects were required to produce a complete point cloud of our
69 test object - the lateral and anterior aspects of the mannequin. The custom written software for
70 the system uses the freely available *Kinect for Windows* (Microsoft, Redmond, WA, USA) Software
71 Development Kit (SDK) to obtain depth maps, from which three-dimensional point clouds of the
72 scene are created using a camera model. The Kinect's depth and colour cameras have a resolution
73 of 640 x 480 pixels and the combined 3D images of our test object produced point clouds comprising
74 approximately 160,000 points. No calibration of the intrinsic parameters of the Kinects was required
75 as a function in the *Kinect for Windows* SDK is used which accesses parameters stored in each
76 Kinect's non-volatile memory.

77 Two 3D point clouds of the scene are produced – one from each Kinect – which required trans-
78 formation (rotation and translation) to produce a complete scan. Several approaches to defining

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

93 Given the two sets of N (in the current study we used a pattern of 11 by 8 squares, producing 70
94 points) corresponding 3D points (p) in each Kinect’s 3D coordinate system (Kinect 1: p_1 , Kinect 2:
95 p_2), the 3x3 rotation matrix (R) and 3x1 translation vector (v) components of the transformation
96 between them were obtained using a common approach based on singular value decomposition
97 [9]. First, the mean location of the points in each Kinect’s **3D coordinate system** were subtracted
98 from the point locations, decoupling rotation and translation. The rotation was estimated by, first,
99 generating a matrix, A :

$$100 \quad A = \bar{p}_1(\bar{p}_2)^T \tag{1}$$

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

$$105 \quad UDV^T = A \tag{2}$$

106 R was then obtained as

$$107 \quad R = VU^T \tag{3}$$

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

$$110 \quad v = m_2 - Rm_1 \quad (4)$$

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

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

122 *2.2. Agreement with manual measurement*

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

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

137 We also measured the surface distance (d) between two points (A and B) on the mannequin
 138 (Figure 3) as these are also important in mammometric analyses [3]. Given a continuous surface
 139 (\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
 140 curve on S between A and B and contained within \mathbf{P} . The system approximates \mathbf{S} as a series of
 141 discrete points $p_{1...n}$. To describe a continuous curve, points between A and B and within 1 mm of
 142 \mathbf{P} were fit with a smoothing spline to give d . Surface distance was minimised by searching possible
 143 values for \mathbf{v} . An initial plane was formed from \overrightarrow{AB} and a normal vector \mathbf{v}_n – calculated using point
 144 cloud data and algorithms from the point cloud library (pointclouds.org) – at either point A or
 145 B , depending on which yielded the lower initial d value. An optimisation routine (a matlab based
 146 gradient descent method) was used to modify \mathbf{v}_n by rotating it about \overrightarrow{AB} until d was minimised.

147 To enable comparison with previously published data using a commercially available 3D surface
 148 imaging system, agreement between manual and Kinect-based system measurements was assessed
 149 using the approach of Catherwood et al. [6]. Agreement was assessed by calculating the mean
 150 and percentage difference between the manual and Kinect-based system measurements [6]. Intra-
 151 rater repeatability was assessed by performing a repeat collection with the system - approximately
 152 20 minutes after the first - and repeating the analysis. The system was dismantled, re-assembled
 153 and re-calibrated before the repeat data were obtained so the intra-rater repeatability includes
 154 an element related to system set-up. Inter-rater reliability was assessed by asking a second rater -
 155 blinded to the analysis of the first rater - to repeat the distance measurements on one 3D image (the
 156 first). In both the intra- and inter-rater analysis, the mean of three measurements was recorded.
 157 Similar to Catherwood, repeatability was assess using the intra-class correlation coefficient (ICC,
 158 ICC(2,1)[?]). The ICCs were supplemented with limits of agreement analysis [10].

159 3. Results

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

166 agreement with manual measurement (Table 3), with a mean difference of 2.2 mm (1.6%) - maximum
167 3.4 mm (3.7 %) and minimum 0.1 mm (0.1%).

168 **4. Discussion**

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

180 Agreement between the digital and manual measurements in the current study is worse than
181 that presented by Catherwood et al. [6]. Catherwood et al. [6] imaged a mannequin - similar size to
182 that used in the present study, with the same anatomical landmarks - using a relatively expensive,
183 commercially available 3D surface imaging system. Mean differences in Euclidean and surface
184 distance of 0.88 mm and 1.36 mm, respectively, were reported. However, we believe that agreement
185 between the Kinect-based system and manual measurements should still be considered acceptable -
186 certainly when the simplicity, accessibility and cost of the Kinect-based system is considered. Like
187 Catherwood et al. [6] - who suggested that a mean difference of 0.88 mm is not clinically significant
188 - we would not expect mean differences between manual and digital measurements of distance of
189 1.9 mm and 2.2 mm to be clinically significant in breast surgery. However, further work is required
190 to establish clinical consensus on what is acceptable accuracy for three-dimensional imaging of the
191 breast. This will allow the usefulness of the Kinect-based scanning system for different applications
192 to be judged.

193 Like other three-dimensional surface imaging systems, the Kinect-based system has several ben-
194 efits over traditional tape/calliper measurements. For example, the time taken to obtain mammo-
195 metric measurements is reduced. Each scan takes approximately two seconds to complete. This

196 has the potential to reduce time requirements for the patient, healthcare staff and the surgeon.
197 Indeed, there is potentially no requirement for the surgeon to be present at the scan; measurements
198 can be taken on the 3D point cloud outside of clinic. Three-dimensional scans can also provide
199 an objective record of the breast, facilitating the planning and evaluation of breast surgery. For
200 example, recently, Quan et al. [11] demonstrated how 3D surface imaging can be used to objectively
201 monitor breast morphology following short-scar medial pedicle breast reduction surgery.

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

212 Our aim during development of the system was to keep the solution as simple as possible.
213 Initial investigations confirmed that one Kinect was not sufficient to capture the full surface of the
214 mannequin and all anatomical landmarks. Two Kinects were sufficient for this purpose but the
215 rigid transformation between them needed to be estimated via a calibration procedure. Several
216 approaches to calibration were possible but we chose to adopt an approach based on a planar,
217 checkerboard calibration object. This method is simple and quick - set-up and collection of the
218 calibration takes less than one minute. Other approaches, similar to that presented by Posada et
219 al. [?], offer the possibility of removing the requirement for a stand-alone calibration, potentially
220 improving the flexibility of the system. Using features of the the object being scanned - with
221 enough surface common to each Kinect - individual point clouds can be registered to produce a
222 complete scan. Future work should explore the application of other approaches to estimating the
223 transformation between the Kinects in the context of breast surface imaging. Regardless of the
224 approach used for calibration/registration, transformation between Kinects introduces a source of
225 error that is not present with only one device. Agreement between manual and digital measurements
226 of distance could be improved by including a third Kinect, placed directly in front of the mannequin,

227 from which most (approximately 70%) of the measurements could be taken in isolation. Only for
228 measurements for which one Kinect does not suffice – such as, for example, those involving the
229 lateral aspect of the inframammary fold – would data from the other two Kinects be used. There
230 would be an increased complexity of the system but this would be minimal and the inclusion of
231 a third Kinect should be explored. Indeed, a third Kinect might be required anyway to capture
232 greater complexity when the system is used to image human breasts. Large ptotic breasts can be
233 problematic for 3D surface imaging systems as they can prevent the capture of the lower pole and
234 inframammary fold [12]. Placing a third Kinect lower, with an upward viewing angle would help
235 address these issues [12, 13].

236 In addition to the greater complexity of the breast surface, there would be other issues when
237 using the Kinect-based system to scan human breast rather than the mannequin used in this
238 study. Movement of participants during the scan - due to breathing and changes in position - is
239 problematic when images from multiple cameras are combined. The duration of the scan with the
240 Kinect-based system presented in this paper is approximately two seconds - during which time data
241 from each Kinect are obtained sequentially. This duration is similar to commercially available three-
242 dimensional imaging systems used in previous mammometric studies [12, 14, 15] which Tepper et al.
243 [12] reported to take approximately two seconds to capture the entire scan area. When the system is
244 used to image human breasts, protocols used in previous studies could be used to reduce participant
245 movement during the scan - with participants having their backs supported by a wall and holding
246 their breath, for example [15]. Additionally, further development/optimisation of the Kinect-based
247 scanning system could reduce the scan duration. Furthermore, point cloud registration techniques
248 (such as that presented by Posada et al. [?]) could help reduce the effects of small movements of
249 the participant. However, further work is required to ascertain how robust these techniques would
250 be to changes in the shape of the torso and breast due to breathing.

251 Distances estimated using the Kinect-based system were compared to manual measurement.
252 There are some limitations of this approach. First, there might be inaccuracies associated with the
253 manual measurement equipment, especially the material tape measure used for the surface distance.
254 Second, for the surface distances, the path defined between two anatomical points could have been
255 different between the manual and digital techniques. The objective function of the optimisation
256 used for the digital data ensured, objectively, that the shortest distance between landmarks was
257 chosen. Ensuring this is the case for manual measurements is difficult. Further, there are obvious

258 practical problems with using a tape to measure curved surface distances. Nevertheless, using
259 manual measurements of distance provided a comparison with what is currently accepted clinical
260 practice [7].

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

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273 Ethical approval: Not required

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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	Umbilicous
16,17	Anterior superior iliac 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.

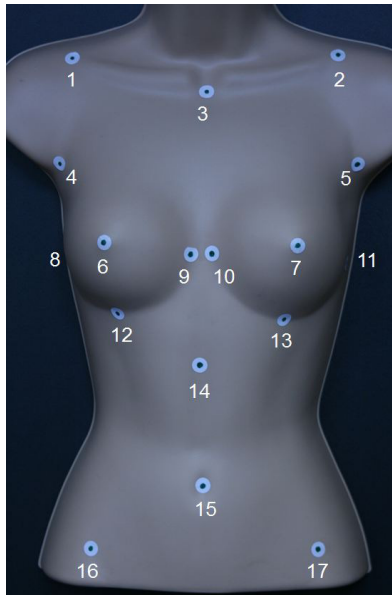


Figure 2: The female mannequin showing the surface landmarks 1-17

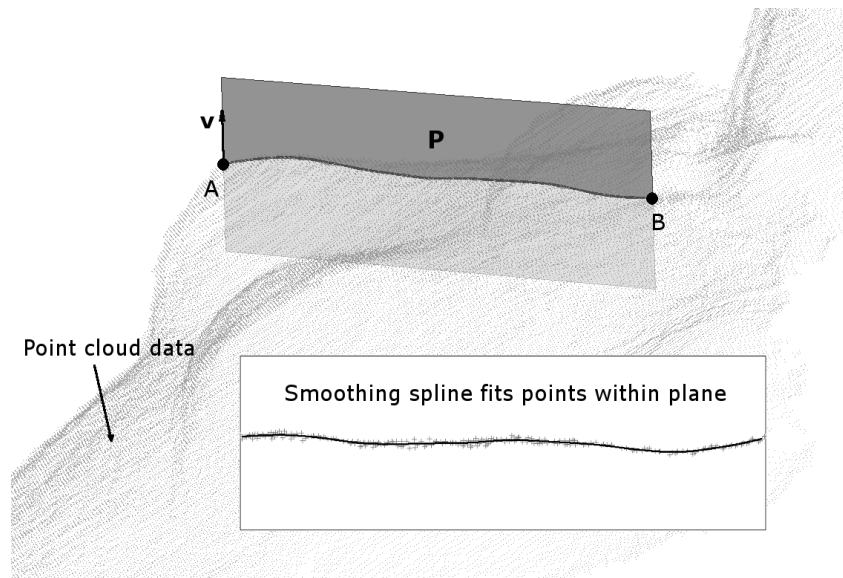


Figure 3: The surface distance is the shortest continuous curve on the point cloud between A and B and contained within P . Shown is the distance between the sternal notch and right nipple. See text for more details

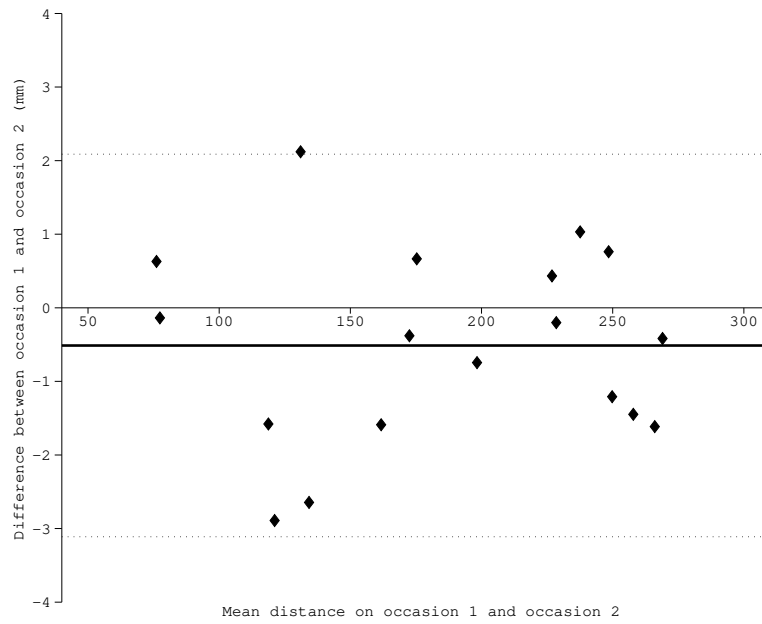


Figure 4: Intra-rater repeatability for 3D Euclidean distance measurements. The solid line is the systematic difference (mean difference) between manual and digital measurements and the dotted lines are the limits of agreement (mean difference ± 1.96 *standard deviation of the differences)

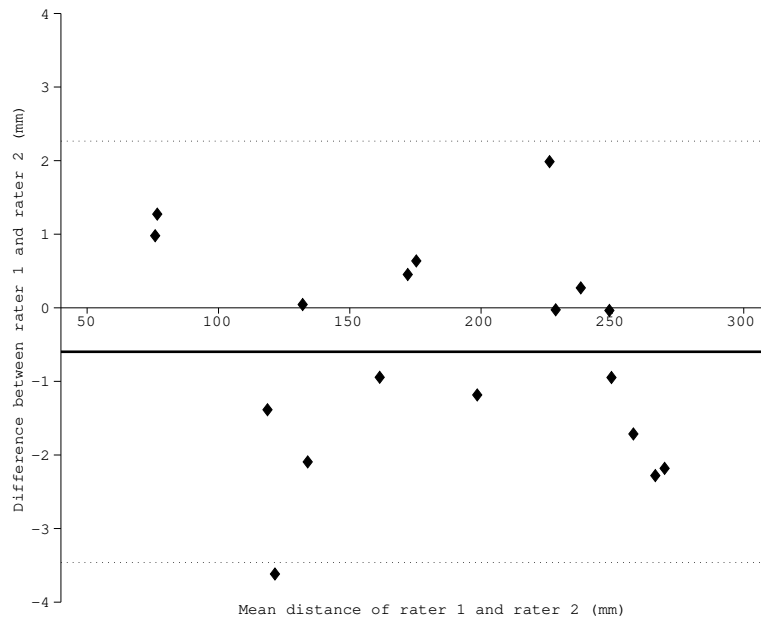


Figure 5: Inter-rater repeatability for 3D Euclidean distance measurements. The solid line is the systematic difference (mean difference) between manual and digital measurements and the dotted lines are the limits of agreement (mean difference ± 1.96 *standard deviation of the differences)