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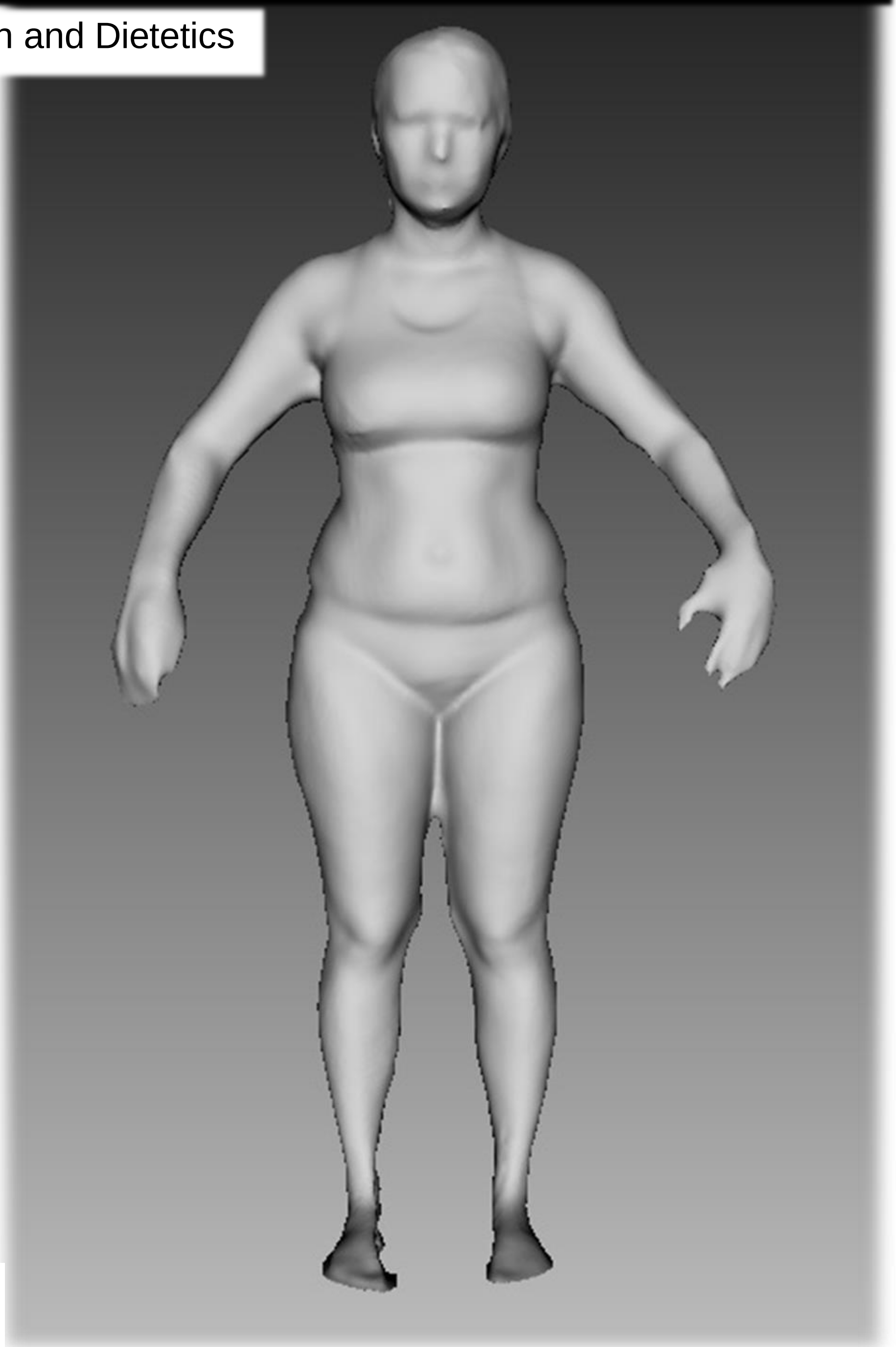
Body volume and circumference measurement with the Microsoft Kinect: comparison with air displacement plethysmography and manual anthropometry

Bachelor thesis for Nutrition and Dietetics



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Body volume and circumference measurement with the Microsoft Kinect: comparison with air displacement plethysmography and manual anthropometry

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Preface

In front of you lies my thesis for the bachelor study Nutrition and Dietetics at The Hague University of Applied Sciences. During the period from September 2015 to January 2016, I set up a study to validate the Microsoft Kinect compared to manual anthropometry and the BODPOD®. This study was a project of the Nutritional Assessment Facility (Nutrition and Dietetics) in collaboration with the 3D scanning facility of Human Kinetic Technology.

The details of this assignment came to me via Blackboard and instantly caught my attention. Since the very first conversation about what the assignment would be, I was determined to accomplish this task. My enthusiasm was therefore very great when I heard I was selected to fulfil this assignment.

This thesis could not have been written without the great support of Jacqueline Langius and Joris van Dam, my principal investigators. They have helped me in any possible way and they put a lot of effort in getting the best result possible. Besides them, I also felt a lot of support from my fellow students and supervising lecturer Elise de Jongh. Not to mention my family and friends, who have listened to my frustrations over and over.

Last but not least this study could not have been done without the volunteers I measured to conduct all the data. Big thanks for them too.

Cécile de Vroomen
Den Haag, January 18th, 2016

Abstract

English

Introduction: Body composition and body circumferences are tools for health professionals to predict health risks and to evaluate a patient's treatment. The BODPOD® is a validated device to determine body composition, but it is expensive and therefore not accessible for a lot of health professionals. Manual anthropometry is used to determine body circumferences. Suspected is that these measurements can be replaced with 3D scanning. Microsoft's Kinect is a device that is able to compose 3D models when combined with the right software. This study poses to validate the Microsoft Kinect combined with Artec Studio 9 and to determine user friendliness.

Methods: Literature research was done to discover the possibilities of the Microsoft Kinect. Findings were that resolution and calibration might be a problem in composing proper 3D models. Compared to other 3D scanning devices, the Kinect was assessed as being promising. The literature search led to the methods for the validation study. 25 volunteers were measured with the Kinect and the comparison method (BODPOD® and manual anthropometry). Artec was used to create the 3D models to take measurements. IBM SPSS Statistics 20 was used to compare both methods, using the Paired Samples T-test, the Intraclass Correlation Coefficient and Bland Altman plots.
User friendliness was determined using three variables: the time scanning took, what amount of scans was needed and how much time adjusting the 3D-models took.

Results: The two methods showed significant difference ($p <0,001$) for all variables with the Paired Samples T-test. Correlation was positive for all variables, variating between 0,366 for upper arm circumference and 0,902 for length. This suggests that the arm circumference measurement is most influenced by noise and length least. The Bland Altman plots showed no proportional or fixed biases. It took about 5 minutes to make a proper scan in on average 1,89 scan attempts. Adjusting and measuring the model took approximately 15 minutes.

Conclusion: The tested method is not applicable for health professionals. The Kinect combined with Artec is, though it is user friendly, not a valid alternative to replace the comparison method. Recommended is to retest the procedure with different software and to retest for reliability too.

Nederlands

Inleiding: Lichaamssamenstelling en lichaamsomtrekken zijn middelen voor gezondheidsprofessionals om gezondheidsrisico's te bepalen en de behandeling van een patiënt te evalueren. De BODPOD® is een gevalideerd apparaat om lichaamssamenstelling te bepalen, maar is erg duur en daarom niet toegankelijk voor veel gezondheidsprofessionals. Antropometrie wordt gebruikt voor het bepalen van lichaamsomtrekken. Verwacht wordt dat deze methodes kunnen worden vervangen door 3D scannen. De Kinect van Microsoft is een apparaat dat 3D-modellen kan maken wanneer gecombineerd met de juiste software. Dit onderzoek tracht de Microsoft Kinect gecombineerd met Artec Studio 9 te valideren en gebruiksvriendelijkheid te bepalen.

Methode: Door middel van literatuuronderzoek werden de mogelijkheden van de Kinect geëxploreerd. Gevonden werd dat resolutie en kalibratie knelpunten zouden kunnen zijn in het vormen van goede 3D-modellen. Vergeleken met andere apparaten om 3D-scans mee te maken, werd de Kinect gezien als een hoopgevende methode. De literatuurresultaten

leidden tot de methode voor het validatieonderzoek. 25 vrijwilligers werden gemeten met de 3D scanner en vergelijkingsmethode (BODPOD® en antropometrie). Artec werd gebruikt om de 3D-modellen te maken en bewerken zodat metingen uitgevoerd konden worden. IBM SPSS Statistics 20 werd gebruikt om de methodes te vergelijken, door gebruik van de Paired Samples T-test, de Intraclass Correlatiecoëfficiënt en Bland Altman-plots. Gebruiksvriendelijkheid werd bepaald door het meten van drie variabelen: de tijd die scannen kostte, hoeveel scans nodig waren en hoeveel tijd het kostte om de 3D-modellen te bewerken.

Resultaten: De twee methoden vertoonden significante verschillen ($p < 0{,}001$) bij alle variabelen met de Paired Samples T-test. De correlatiecoëfficiënt was positief voor alle variabelen, variërend tussen 0,366 voor de armomtrek en 0,902 voor de lengte. Dit suggereert dat de meting van armomtrek het meest gevoelig is voor ruis en de lengtemeting het minst gevoelig. De Bland Altman-plots vertoonden geen vaste of proportionele bias. Het kostte ongeveer 5 minuten om een bruikbare scan te maken in gemiddeld 1,89 pogingen. Het bewerken en meten van de modellen kostte ongeveer 15 minuten.

Conclusie: De geteste methode is niet bruikbaar voor gezondheidsprofessionals. De Kinect gecombineerd met Artec is, ondanks zijn gebruiksvriendelijkheid, geen valide alternatief ter vervanging van de vergelijkingsmethode. Aangeraden wordt om de procedure te hertesten met andere software en te testen op betrouwbaarheid.

Content

1. Introduction

Body composition and body circumferences are measurements used by health professionals like dieticians to predict health risks and to evaluate treatment. Waist circumference, for example, predicts the risk for Diabetes type II and cardiovascular diseases(1-3).

The traditional way of measuring body composition is by volume measurement. In the past this was done with hydrodensitometry, but nowadays air displacement plethysmography is used for volume measurement. When one knows the body volume, body composition can be calculated by equations(4). The BODPOD® is a validated device that uses air displacement plethysmography for determining body composition. Although the BODPOD® is more expensive than hydrodensitometry, it is easier to use for the professional and less stressful for the subject than measuring by hydrodensitometry(5).

Suspected is that 3D scanning is a new approach to measure body volume. A 3D scanning device composes a 3D model, which is a copy of the subject that was scanned. The 3D model contains information such as body volume and body circumferences. The advanced devices are, like the BODPOD®, costly. Nevertheless, through development within gaming industry more inexpensive devices for 3D scanning arise. Different methods of 3D scanning became available: 3D laser scanning, photonic 3D scanning, infrared technology and structured light technology are the most used examples.

Several studies(6-8) investigate the reliability and validity of the 3D laser scanning method. Daanen and Ter Haar compared different 3D body scanners working with different scanning methods. In their review they have evaluated laser line technology, structured light technology, infrared technology, stereo photogrammetry and combinations of these methods. Their study intended to find a way to fit people the best-fitting clothes. They found an increase in resolution of the 3D scanners over the past 15 years. Besides that, the scanners are all easy to use, but lack the accuracy that is required for tight fitting garments(6). According to Reese Pepper et al the 3D laser scanning method is a quick, simple to use and inexpensive method of body composition analysis(7).

Wells et al compared 3D-models based on photonic scanning with the Hamamatsu Bodyline Scanner (HBS) to underwater weighing and air displacement plethysmography. They found that although the HBS cannot yet measure body volume with sufficient accuracy to predict fatness, much of the error is probably due to difficulties in standardizing lung volume during the scan. Besides that, making the models watertight is also an important source of error. Wells et al developed fully automatic surface-skinning algorithms, which provide a smooth surface representation and allow modelling of tangency discontinuities(8).

3D scanning based on structured light technology is another promising method. Microsoft's Kinect is an example of a device based on a combination of structured light technology and infrared technology(9). With Kinect and the right software, body volume can be determined by 3D body scanning. Kinect could be an inexpensive alternative for healthcare professionals who do not have access to a costly device like the BODPOD®. To illustrate: the Kinect costs, including the right software and a computer that is able to run the software, about €1500. The BODPOD® costs €50.000. So, the Kinect costs 2 percent of buying a BODPOD®. Due to the high cost, there are only a few BODPOD's available in The Netherlands. Therefore, only a small percentage of the Dutch dieticians have access to a BODPOD® to measure their clients(10).

Whether Kinect is a useful and user friendly alternative for determining body composition is yet to be investigated. Although studies have been done in the areas of gaming(11), ergonomics(12) and sports(13), almost none are within the area of body composition and body volume(14). This is the main reason why this study proposes to determine the user friendliness and validity of volume measurement through Kinect, with the BODPOD® as a reference for comparison. Besides, the study will explore whether the Kinect is a valid and user friendly alternative for measuring waist-, hip- and upper arm circumferences. These measurements, called anthropometry, are mostly done by dieticians manually(15).

Because of the lack of studies within the area of body composition and volume, there is no manual for 3D body scanning available. The present study will aim to assemble a manual for 3D body scanning and adjusting the results to make them usable for analysing body composition. Compared to an expensive device as the BODPOD®, the more inexpensive Kinect is accessible for smaller institutions and self-employed dieticians. Besides that, the Kinect is supposed to perform multiple measurements in fewer steps. This should make the process of determining body composition easier and more efficient(10).

1.1 Purpose

The present study aims to determine whether the Kinect is a user friendly, valid alternative to measure body volume for health professionals like dieticians. If so, health professionals would have a new approach to calculate body composition. The knowledge of body composition allows a dietician to specify a diet on his patient’s individual needs, instead of using formulas that are not person specific. That could lead to more efficient treatment.

This study results in an article on the findings, a manual on the scanning process and the graduation file as described by The HU of Applied Sciences. The article can be found in appendix 1 and the manual can be found in appendix 2.

1.2 Research questions

The main question this study will focus on is: *Is the Microsoft Kinect combined with Artec Studio 9 a valid and user friendly alternative for measuring body volume and upper arm-, waist- and hip circumference compared to air displacement plethysmography and anthropometry?*

The study is divided in a literature- and a validation study. The literature study answers the following sub question:

i. Is the Kinect able to create a 3D model in which volume and circumference can be measured?

The practical study answers the following sub questions:

ii. Are volume and circumferences from the models made by the Kinect similar in repeated measurements?
iii. How convenient is the Kinect for measuring body volumes in terms of validity, accuracy and user friendliness compared to air displacement plethysmography?
iv. How convenient is the Kinect for measuring upper arm-, waist- and hip circumference in terms of validity, accuracy and user friendliness compared to anthropometry?

1.3 Operationalization of concepts

Valid/validity = whether the device measures the desired characteristics. Validity is measured by comparing the Kinect's results with air displacement plethysmography and anthropometry.
Accuracy = whether the device's results are the same as those measured with the reference device. Accuracy is measured by comparing the Kinect's results with air displacement plethysmography and anthropometry.
User friendliness = whether the device is understandable and easy to use for the health professional. User friendliness is measured by registering how much time scanning costs, what the amount of failed scans is per participant and how much time it costs to adjust the 3D-model to be useable.

2. Literature study

2.1 Methods

Is the Kinect able to create a 3D model in which volume and circumference can be measured? For answering this question the following online databases were consulted: PubMed, Cochrane Library, Google Scholar and CINAHL Plus. The “snowball’-method was used to gain more sources.

Search terms were divided into two groups: a group of terms related to the device and a group of terms related to the alleged use. Terms from the first group were combined with terms from the second group. Search terms were:

- Relating to the device: “3D scan*”, Kinect,
- Relating to the alleged use: volume, circumference, “cubic measure”, dimensions, capacity, bounds, outline(s), girth

In order to ensure the reliability and usability of the literature study relevance determines whether the source is useable. Relevance was in first instance determined by assessing the title and abstract. When assessed as being relevant, the article was read properly and the useful information was highlighted. Literature in other languages than English or Dutch were excluded. Due to the expected small amount of useful literature publication date was not an exclusion criterion. The evidence level of the sources that were used is to be found in appendix 3.

2.2 Results

To determine the usability of the Kinect a literature search was set up. The methods for the validation study were based on the results found in this literature search. The found literature will be set out in this paragraph. The results of this literature search are explained ranked by the scanning difficulty and amount of subjects and comparability with the present study. The results shown last are most comparable to the present study and/or have highest level of evidence.

2.2.1 Resolution and calibration

Dellen and Rojas conducted a study in 2014 to determine the Kinect’s usefulness in volume intersection. Their study focussed on scanning household objects such as cans, tins and boxes. Each object was scanned from 4 sides and the images were put together to create a copy of the original object. This was done using point clouds, which are maps with coordinate points on it. The deviation of these points during scanning is what makes the scanner able to determine dept. To extract point clouds for each view, they used the Point Clouds Library (http://pointclouds.org). In their study, they compared the measurements of the Kinect with manual measurements and found that the Kinect is suitable to measure volume of different objects, but that it is less suitable for smaller, detailed objects. An average error percentage of 5,2% was found. They conclude that this is mostly due to the low resolution of the Kinect camera(16).

That conclusion was also found by Khoshelham and Oude Elberink. Their research focussed on the calibration of Kinect-like 3D scanners. The Kinect-like scanners are based on two cameras: an infrared (IR) camera and a red-green-blue (RGB) camera. The infrared camera is the camera measuring depth with point clouds. The RGB camera is used for very accurate colour image acquisitions. These cameras together form the 3D model. To eliminate distortions in the point cloud and misalignments between the colour and depth data an accurate stereo calibration of the IR and RGB camera is necessary. They also found that the error of depth measurements increases quadratically with increasing distance from the sensor. Besides the increasing error in depth measurements, the depth resolution also decreases quadratically with increasing distance from the sensor(17).

2.2.2 Scanning human(like) subjects

Wan et al 3D scanned non-living humanlike mannequins to test the accuracy of the Kinect in 2013. They compared the results from the Kinect with the known measurements of the mannequins. Besides they compared results from rescanning the mannequins multiple times with one Kinect. They found that Kinect scanning is a time-saving method of composing a model to measure body volume and calculate body composition. The Kinect was 97,7% accurate for dimension measurement and 96,8% accurate for volume measurement. They found no systematic under- or overestimation in volume with the Kinect(18).

Clarkson et al conducted a study similar to Wan et al, but their study recruited twelve living male participants. Their measurements focussed on scanning the torso with the Kinect. The participants were asked to hold their breath during the measurements to minimize the influence of breathing. The relative technical error of measurement was calculated across 3 repeated scans and showed to be on average 0,88% (±0,1). Relative accuracy was quantified by calculating intraclass correlation coefficients, using a two way random effects model with single measures accuracy to be 0,997. In this study, the 3D scanning system overestimated volume with 0,04% (±2,11) when compared with the gold standard laser scan(19).

Tong et al found that the quality of their reconstructed models is still poor for some specific applications due to low quality of depth data captured by Kinects. The error with the Kinect is 1,5 to 6,2 centimetres in different body segments compared to biometric measures. Although the quality is not so good, their method and the algorithm they developed is efficient and can generate convincing 3D human bodies at a relatively low price and has good potential for virtual try on systems or personalized avatars(20). Although that is not the purpose this present study aims for, it shows the accuracy of the Kinect and was therefore assessed as being useful.

The study that Weiss et al conducted showed that a single, inexpensive 3D scanner can achieve similar accuracy as a system based on multiple calibrated cameras and structured light sources. For this study they used the Kinect as the 3D scanning device and compared this to the Vitus Laser Scanner. On average, the Kinect differed 10,17mm from the Vitus. They found that measurements of the body can be reliably predicted using a simple linear regression approach and compare favourably to expensive commercial systems(21).

Menna et al found the Kinect device to be a breakthrough solution with respect to range-imaging sensors, primarily due to its costs but also thanks to its quite satisfactory metric performances for close-range applications where some millimetre accuracy is more than sufficient(22).

2.2.3 Comparing Kinect to other approaches

According to Clarkson et al, who compared the Kinect to the gold standard 3D laser scan in measuring the trunk volume, the results show a very small average difference in the volume measurements obtained with the Kinect scanning system. However, the standard deviation in the error means that on some occasions the accuracy is slightly less than that of the Yeadon model. The mean error of the Kinect based system in volume measurement was 0,04% with an standard deviation of 2,11. The Yeadon model had an error in volume measurement of -1,17%(23).

In September 2015, Soileau et al published an article in which they explained their study comparing a Kinect-based 3D imaging method to a reference 3D laser imaging system. They found that the Kinect-based method measured some dimensions with high correlations to the laser system, like large linear, circumferential, volume and surface areas. At the other hand, mean measurement differences were substantially larger for small structures. The conclusion was that the Kinect, as a relatively low cost device, provides anthropometric and related body dimensions comparable to those of larger anatomic structures evaluated with a reference laser system(24).

3. Validation study

3.1 Methods

3.1.1 Study design

The present study was designed as a quantitative cross-over comparison. Data for the present study consisted of the measurements of the participants with the 3D scanner as well as the BODPOD® and the manually measured anthropometrics. Data was collected from October to December 2015 at The Hague University of Applied Sciences.

3.1.2 Participants

Participants were recruited in the same period as data collection. Recruitment was carried out through a message on social media, the HHS portal and within the personal network of the recruiter. Participants were able to schedule their appointment via an online timetable. The study attempted to conduct a population as heterogenic as possible, to test whether the results of the Kinect depend on different body forms. An overview of the inclusion- and exclusion criteria is to be found in table 1. Limitations that were used as a guideline(25) to determine participant criteria are listed below:

- The BODPOD® is only useable for people with a weight under 250kg.
- For the scale that belongs to the BODPOD®, it is necessary that the person that is measured is able to stand still.
- Claustrophobic people will be excluded from the study, because of the small space in the BODPOD®.
- Physically disabled people are excluded too, since the BODPOD® is not validated for this group.
- Children are excluded as participants because they cannot give legal consent to participate.

Table 1 Inclusion- and exclusion criteria

Inclusion criteria	*Exclusion criteria*
Adults (age ≥ 18)	People who cannot stand on their own
	Physically disabled people
	People heavier than 250kg
	Claustrophobic people

3.1.3 Measurements

The study focussed on measuring and comparing body volume and body circumferences. Volume and circumferences were measured multiple times to check if retesting gave similar results and to rule out inaccuracy. Body volume was measured with a Kinect and the BODPOD®, body circumferences were measured with Kinect and manual anthropometry. Participants were measured twice by the BODPOD®. If the two volume measurement had inconsistent results, a third measurement was conducted. This was determined by the in the BODPOD® implemented rules for maximum deviation.

Although some characteristics are no reason to exclude people from the study, some of them (age, gender, ethnicity, BMI) were noted for evaluation purposes.

3.1.4 Method of data collection

For data collection the steps below were followed. All steps were carried out by one student trained in 3D scanning in order to increase accuracy. The measuring set was derived from the one used by Wan et al(18, figure 1).

1. Every day that data were collected, the BODPOD® and the scale that belongs to it were calibrated following the steps implemented in the BODPOD's software following the BODPOD's manual(25).
2. Before starting the actual measurements every participant was asked some background questions (appendix 4). These questions included the characteristics that were mentioned before: age, gender and ethnicity. Participants were asked to go to the toilet if they had not been recently.
3. Participants were asked to change to their swimsuit or similar clothing.
4. To calculate the BMI, length was measured on sight, as well as weight. Weight was determined with the scale that belongs to the BODPOD®, which is accurate to three decimals. The participants wore their swimsuit during the weighing.
5. The professional measured upper arm-, waist- and hip circumference with a Seca 201 tape-measure twice manually as described in 'Het Dietistisch Consult' by Becker-Woudstra et al(26).
6. The participant was asked to take place in the BODPOD®. The BODPOD® measurement took place. Lung volume was estimated by the BODPOD® as described in its manual(25).
7. The participant was scanned with the Kinect until a proper model was formed as described in appendix 2.
8. The professional adjusted the raw 3D-model as described (appendix 2). The 3D-model was used to measure volume and upper arm-, waist- and hip circumference.
9. The professional entered the results in SPSS. The variables that are set are: gender, length, weight, BMI, ethnicity and the different volume and anthropometric measurements as mentioned above (appendix 4).

The 3D scans were made with the software Artec Studio 9 (http://www.artec3d.com/software/artec-studio-10#compare-studios). This software was used to create and adjust the models as well as to do the measurements. When it was not possible to fill all the holes in Artec Studio, Netfabb was used to measure the volume of the model. Netfabb (http://www.netfabb.com/) is software used for 3D printing and is therefore able to fill all the holes.

For the first three and the last three subjects, the time the scanning procedure took was registered. These values were used to determine the average scanning time.

The results were checked by fellow students. This use of critical peer consultation is an help in the process of checking whether mistakes or erroneous assumptions were made(27).

3.1.5 Method of data processing

The collected data was processed by using IBM SPSS Statistics 20, in which the variables as presented in appendix 4 were entered. The variables gender, length, weight, BMI and ethnicity were descriptive variables. These variables were used to determine the heterogeneity of the population. The other variables were used to compare the different measurement methods. For the repeated tests, the average of the results was calculated.

The paired variables as shown in table 2 were analysed with a Paired Samples T-test. Length was used to compare the different measuring methods. The Intraclass Correlation Coefficient was calculated using an absolute agreement definition. The Bland Altman plot was used to show analogy between the numeric variables: arm-, waist- and hip circumference, length and volume. This test displays the agreement between the results by the Kinect and the BODPOD® or manual anthropometry. The Bland Altman test was repeated for every pair of variables.

Table 2 Variable pairs used for the Paired Samples T-test and the Bland Altman Plots

Pair	*Variable 1*	*Variable 2*
1	MAN_arm	KINECT_arm
2	MAN_waist	KINECT_waist
3	MAN_hip	KINECT_hip
4	BODPOD_volume	KINECT_volume
5	Length	KINECT_length

The hypotheses was: H0 = There is no significant difference in the results from the Kinect and the BODPOD® & anthropometry. H1= There is a significant difference in the results from the Kinect and the BODPOD® & anthropometry.

3.3 Results

3.3.1 Subjects

Subject characteristics are presented in table 3. In total 25 Caucasian subjects were included in this study, 4 male and 21 female participants. Except for two subjects, one man and one woman, all subjects had a healthy BMI (18-25 kg/m²).

Table 3 Subject characteristics

	Men (n=4)			*Women (n=21)*			*Total (n=25)*		
	min	max	mean	min	max	mean	min	max	mean
Age (years)	20	43	27,5 ±10,5	18	34	21,5 ±3,6	18	43	22,4 ±5,5
Length (m)	1,79	1,87	1,81 ±0,03	1,57	1,83	1,69 ±0,06	1,57	1,87	1,71 ±0,07
Weight (kg)	74,4	91,2	79,4 ±7,9	48,9	76,0	63,1 ±7,6	48,9	91,2	65,7 ±9,7
BMI (kg²/m)	23,0	26,2	24,1 ±1,5	18,4	25,2	22,1 ±2,0	18,4	26,2	22,4 ±2,0

3.3.2 Between-method evaluations

The results from the manual anthropometries, BODPOD® volume measurements and Kinect-based measurements are to be found in table 4.

Table 4 Comparison of circumference, volume and length measured by Kinect and comparison method. Significance represents the difference between the methods. Correlation represents the Intraclass Correlation Coefficient as described.

	Manual or BODPOD®	*Kinect*	*Difference*	*Significance*	*Correlation*
Circumferences (cm) n=24					
Upper arm	26,6 ±2,1	30,1 ±3,1	3,5 ±2,2	<0,001	0,366
Waist	73,2 ±6,8	80,2 ±6,2	7,0 ±1,3	<0,001	0,618
Hip	98,0 ±5,9	104,6 ±5,5	6,6 ±2,0	<0,001	0,564
Volume (l) n=23	63,9 ±9,6	76,6 ±11,6	12,7 ±3,1	<0,001	0,560
Length (m) n=25	1,71 ±0,07	1,74 ±0,07	0,03 ±0,0	<0,001	0,902

Correlation

The intraclass correlation coefficient suggests a weak positive linear relationship in upper arm circumference, a moderate positive linear relationship in waist- and hip circumference and volume and a very strong positive linear relationship in length (28). These values suggest that the upper arm circumference is most influenced by noise, length on the other hand has nearly no influence of noise.

Bland Altman plots

The Bland-Altman plots reveal the bias of the Kinect based measurement compared to the comparison method. This is shown in figure 1 to 5. The Bland Altman plots show the Kinect measured higher values for all participants than the comparison method. No proportional or fixed bias can be reliably interpreted from the figures, though the figures suggest possibility of a proportional bias with the trend of the difference being increased as mean circumference increases. The plots also show various degrees of deviation. Some body segments seem to be more influenced by overestimation than others.

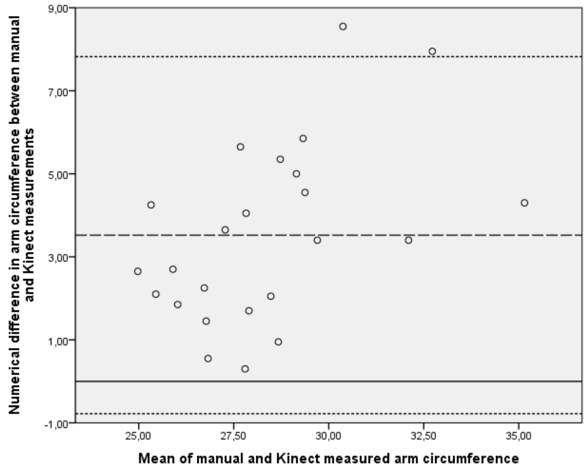

Figure 1 Bland Altman plot of the arm circumference. The X-axis contains the mean arm circumference (mean from the manual and Kinect measurement). The Y-axis contains the numerical difference in arm circumference between the manual and Kinect measurements. The upper and lower dashed lines are ±2SD-lines. The middle dashed line is the mean of Y. The solid line is the origin (0).

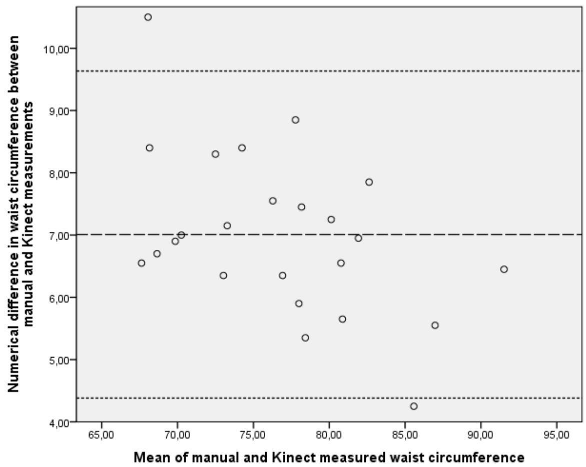

Figure 2 Bland Altman plot of the waist circumference. The X-axis contains the mean waist circumference (mean from the manual and Kinect measurement). The Y-axis contains the numerical difference in waist circumference between the manual and Kinect measurements. The upper and lower dashed lines are ±2SD-lines. The middle dashed line is the mean of Y.

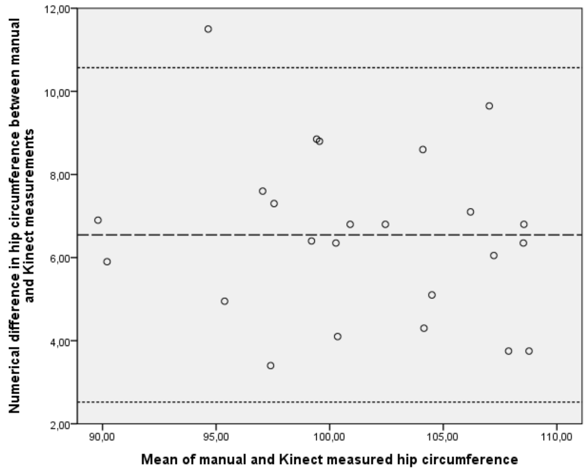

Figure 3 Bland Altman plot of the hip circumference. The X-axis contains the mean hip circumference (mean from the manual and Kinect measurement). The Y-axis contains the numerical difference in hip circumference between the manual and Kinect measurements. The upper and lower dashed lines are ±2SD-lines. The middle dashed line is the mean of Y.

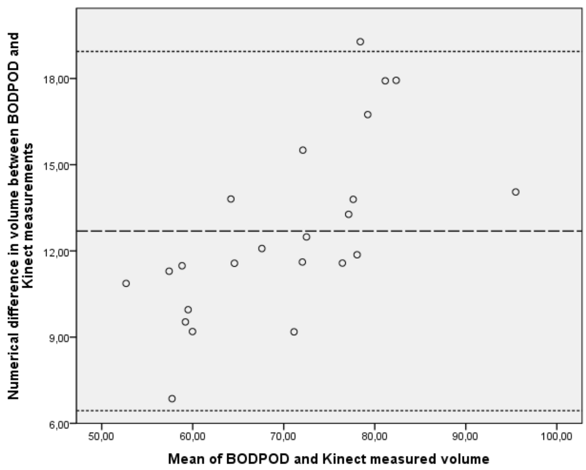

Figure 4 Bland Altman plot of the volume. The X-axis contains the mean volume (mean from the BODPOD and Kinect measurement). The Y-axis contains the numerical difference in volume between the BODPOD and Kinect measurements. The upper and lower dashed lines are ±2SD-lines. The middle dashed line is the mean of Y.

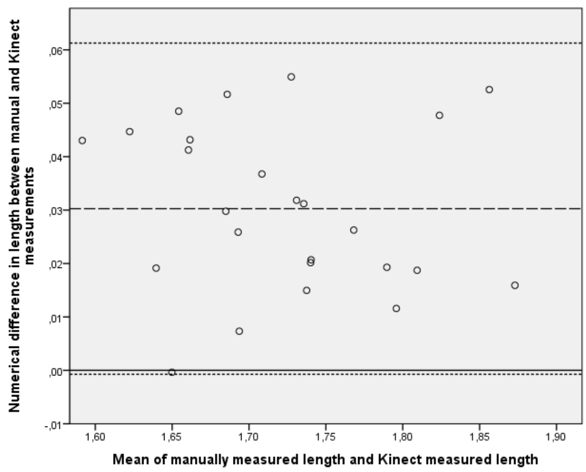

Figure 5 Bland Altman plot of the length. The X-axis contains the mean length (mean from the manual and Kinect measurement). The Y-axis contains the numerical difference in volume between the manual and Kinect measurements. The upper and lower dashed lines are ±2SD-lines. The middle dashed line is the mean of Y.The solid line is the origin at 0,00.

3.3.3 User friendliness

User friendliness is divided into three measurable categories, namely how much time scanning takes, what the amount of failed scans is per participant and how much time it takes to adjust the 3D-model to be useable for measuring. The BODPOD® measurement takes about 10 minutes, which does not include the time to calibrate it. The manual anthropometry took about 5 minutes in this study.

In the beginning, scanning one model took the professional about 20 minutes. The scanning time decreased during the scanning period, ending with the professional being able to make a useful scan in averagely 5 minutes.

It took the professional on average 1,9 ±1,2 scans to create a proper 3D model. In more than 50% of the subjects more than 2 scans were needed. The amount of scans needed, became more consistent and decreased during the data collection period. Figure 6 shows the frequency of scan attempts and the missing values.

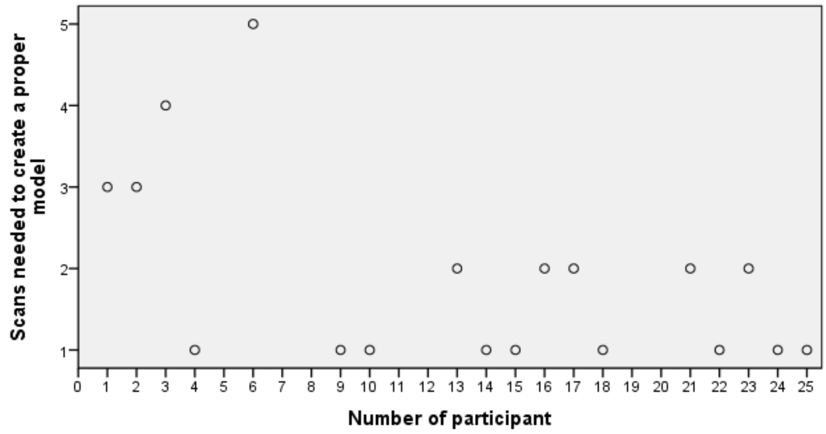

Figure 6 The frequency of scan attempts per participant (n=18). Every dot represents a participant. The dashed line represents the trend line.

The time needed to adjust the 3D model decreased during the scanning period, starting with about 45 minutes and ending with approximately 15 minutes. These 15 minutes consisted of the time the computer needed to render the model as well as processing the manually given commands. In total the procedure takes 20 minutes per 3D model at the end of the scanning period.

4. Discussion and recommendations

4.1 Conclusion

This study compared air displacement plethysmography and manual anthropometry with measurements with the Kinect combined with Artec Studio 9. This study was done to validate the Kinect as an alternative for air displacement plethysmography and manual anthropometry. This would give more health professionals access to a device for the measurement of body volume in order to evaluate body composition.

The literature suggests that the Kinect is a promising alternative for volume measurement. Although calibration is a critical problem and the resolution of the cameras in the Kinect is poor, the results from the Kinect do not differ very much from reference laser systems.

In conclusion, this study shows that the method used in this study is not applicable for health professionals. The Kinect, combined with Artec, is not a valid alternative for measuring body volume and upper arm-, waist- and hip circumference compared to air displacement plethysmography and manual anthropometry.

There is a significant difference between the manual and BODPOD® measurements and the Kinect measurements. The correlation coefficients suggest weak to very strong positive linear relationships, but the Bland Altman plots do not reflect. Therefore the null hypotheses can be rejected.

The method is, after some training, user friendly. On all three categories, the Kinect scores satisfactory: it takes the professional about the same amount of time to measure one with the BODPOD® and manual measurements as with the Kinect and the adjustment of the model.

4.2 Discussion

The present study was the first one to compare the Kinect's measurements to both the BODPOD and manual anthropometry. Other studies compared the Kinect to other 3D scanning devices and/or manual anthropometry and/or known measurements. The comparison to the BODPOD and manual anthropometry made the results of this study new and innovative. Though the methods resulted in significantly different values, the Kinect still seems to be auspicious.

The significant difference between the methods could have had some reasons. First, the study did not correct for possible movement of the participants by algorithm. Neither were the participants asked to hold their breath. The professional tried to correct for movement when adjusting the models. This could have led to adjusting too much or too little and to overestimation in the 3D models. The proposed method still overestimated all variables for all participants, so this was not of major influence.

Besides that, the method for adjusting the models slightly changed twice during the scanning period. Unlike what the professional thought, this change of method did not decrease the percentage difference between the methods, as shown in figure 7. Figure 7 shows the percentage difference of hip circumference, the other variables show similar results.

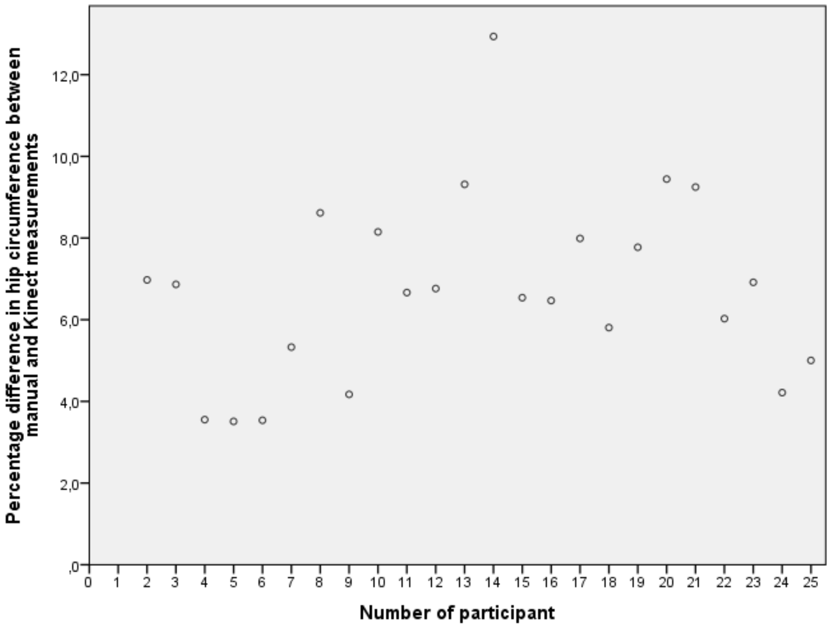

Figure 7 Scatter plot of the percentage difference between the methods. The X-axis contains the case numbers. The Y-axis contains the percentage difference between the manual and Kinect hip circumference measurements.

The professional noticed, during the adjustment of the models, that the lower legs were a crucial part in creating a proper model. When making the model watertight for volume measurement, it seemed that the lower legs lacked detail and in some cases the software cut them off to achieve water tightness. In other cases, where the inside of the limbs were not scanned completely, the software filled them in itself. This led to inaccurate estimations, resulting in flipper-like connections between the arms and torso and between the legs. This might have led to overestimation of the volume and a decrease in accuracy of the upper arm circumference measurement.

Besides what has been mentioned before, this study did not calibrate the Kinect before starting. The error that might have occurred by not calibrating the Kinect corresponds with the previously mentioned study by Khoshelham and Oude Elberink(17).

Furthermore, not all subjects did follow the quite strict body clothing protocol that is used for the BODPOD®. All subjects wore spandex clothing, like bikinis, swimsuits or running pants. Fields et al. described in their study, focussing on the influence of body clothing, that a tight fitting swimsuit gives most accurate results. Different clothing translates to a difference of fat mass up to more than five percent(29). Though the clothing could have influenced the results from the BODPOD, the great differences and overestimation from the Kinect are still too much to be reconsidered valid. Different body clothing in the BODPOD should decrease the difference between the results and that is not apparent from the results.

Although the population consisted solely of young Caucasians with a healthy weight, it is plausible that the results of this study are generalizable for all people. The population had a fairly easy body shape for scanning, Daniell et all describe increasing pelvis and abdomen volumes with increasing weight(30). This might have influence on the overestimation of the proposed method. That suggests that the deviation between the methods should be less for people with a fairly easy body shape. Since there were no overweight participants, it is only likely to think that the deviation is even greater for them.

4.3 Recommendations

The landmarks to measure the circumferences were determined based on visual characteristics of the subjects. A recommendation would be to retest with the use of software or algorithms that are able to automatically locate these landmarks, for example the algorithm from Ben Azouz et al(31). This would decrease the chance of incorrect measurements. Since the professional assessed all participants similarly, it is not likely that this would have influenced the results in the present study so much that the outcome would be different.

When comparing to the found literature, one of the main differences is the software this research used. Therefore a recommendation would be to retest the procedure with different software, for example the SkanLab as described by Buffa et al(32). Furthermore, it would be recommendable to test for reliability of the proposed method. Though the proposed method is not valid enough to be applicable for health professionals, it could be of great use in the future. Further investigation should reveal this.

Finding a cheap, valid, reliable alternative for the BODPOD® and manual anthropometry would give more health professionals access to a device for determining body composition and body circumferences. This would make it easier to determine health risks and it would help health professionals to adapt treatment to individual needs.

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Appendices

Appendix 1. Article

Article: Body volume and circumference measurement with Microsoft Kinect: comparison with air displacement plethysmography and manual anthropometry

Objective: Whole body 3D scanning, a new method to determine body composition and circumferences, was compared to air displacement plethysmography (using the BODPOD) and manual anthropometry in 25 young adults.
Design: quantitative cross-over comparison
Subjects: 25 healthy Caucasian adults
Measurements: Body volume in litres via Microsoft Kinect and BODPOD, body circumferences and length in centimetres via Microsoft Kinect and manual anthropometry.
Hypotheses: H0=There is no significant difference in the results from the Kinect and the BODPOD® & anthropometry.
Results: The two methods showed significant difference (p <0,001) for all variables with the Paired Samples T-test. Correlation was positive for all variables, variating between 0,366 and 0,902. The Bland Altman plots showed no proportional or fixed biases.
Conclusion: The tested method is not applicable for health professionals. The Kinect combined with Artec is not a reliable and valid alternative to replace the comparison method. Recommended is to retest the procedure with different software.

Introduction

Body composition and body circumferences are a tool for health professionals like dieticians to predict health risks. Waist circumference for example is a way to predict ones risk for Diabetes type II and cardiovascular diseases(1-3). The traditional way of measuring body composition is by volume measurement. In the past this was done with hydrodensitometry (immersing someone completely under water and measuring how much the water level has risen), but nowadays air displacement plethysmography is used. When one knows the body volume, body composition can be calculated(4). The BODPOD® is a validated device that uses air displacement plethysmography. Although the BODPOD® is more expensive than hydrodensitometry, it is easier to use for the professional and less stressful for the subject than measuring by hydrodensitometry(5).

It is suspected that 3D scanning is a new way to measure body volume. A 3D scanning device composes a 3D model, which is a copy of the subject that was scanned. The 3D model contains information like body volume and body circumferences. The advanced devices are, like the BODPOD®, costly. Nevertheless, through development within gaming industry more inexpensive devices for 3D scanning arise. Different methods of 3D scanning are available, such as 3D laser scanning and photonic 3D scanning. Several studies(6-8) investigate the reliability and validity of the 3D laser scanning method. Daanen and Ter Haar compared different 3D body scanners working with different scanning methods. They found an increase in resolution of the 3D scanners over the past 15 years and the scanners are all easy to use, but lack the accuracy that is required for tight fitting garments(6). According to Reese Pepper et al the 3D laser scanning method is a quick, simple to use and inexpensive method of body composition analysis(7).

Wells et al compared 3D-models based on photonic scanning to underwater weighing and air displacement plethysmography. They found that although the device cannot yet measure body volume with sufficient accuracy to predict fatness, much of the error is probably due to difficulties in standardizing lung volume during the scan. Besides that, occlusion is also an important source of error[8].

3D scanning based on structured light technology is another promising approach. Microsoft's Kinect is an example of a device based on structured light technology[9]. With Kinect and the right software, body volume can be determined by 3D scanning a body. Kinect could be an inexpensive alternative for healthcare professionals who do not have access to a costly device like the BODPOD®.

Whether Kinect is a useful and reliable alternative for determining body composition is yet to be investigated. This is the main reason why this study proposes to determine the validity of volume measurement through Kinect, with the BODPOD® as a reference for comparison. Besides, the study will explore whether 3D scanning is a valid alternative for measuring waist-, hip- and upper arm circumferences. These measurements, called anthropometry, are done by dieticians mostly manually[10].

Compared to an expensive device as the BODPOD®, the more inexpensive Kinect is accessible for smaller institutions and self-employed dieticians. Besides that, the Kinect is supposed to perform multiple measurements in fewer steps. This should make the process of determining body composition easier[11].

Hypothesis was: there is no significant difference in the results from the Kinect and the BODPOD® & anthropometry.

Methods

The present study was designed as a quantitative cross-over comparison. Data for the present study consisted of the measurements of the participants with the 3D scanner as well as the BODPOD® and the manually measured anthropometrics. Data was collected from October to December 2015 at The Hague University of Applied Sciences.

25 participants were recruited in the same period as data collection. Recruitment was carried out through a message on social media, the HHS portal and within the personal network of the recruiter. The limitations of the BODPOD®[12] were used as guideline and all used limitations are listed below.

- The BODPOD® is only useable for people with a weight under 250kg.
- For the scale that belongs to the BODPOD®, it is necessary that the person that is measured is able to stand still. This is necessary for the 3D scan too.
- Claustrophobic people will be excluded from the study, because of the small space in the BODPOD®.
- Physically disabled people are excluded too, since the BODPOD® is not validated for this group.
- Children are excluded as participants because they cannot give legal consent to participate.

The study focussed on measuring and comparing body volume with a Kinect and the BODPOD®. Volume and circumferences were measured multiple times, from the 3D model as well as manually, to check if retesting gave similar results and to rule out inaccuracy. The BODPOD® measured the participants twice and if the results are inconsistent three times.

Although some characteristics are no reason to exclude people from the study, some of them (age, gender, ethnicity, BMI) were noted for evaluation purposes.

For data collection the steps below were followed. All steps were carried out by one student trained in 3D scanning in order to increase accuracy and reliability. The measuring set was derived from the one used by Wan et al(13, figure 1).

10. Every day that data were collected, the BODPOD® and the scale that belongs to it were calibrated following the steps implemented in the BODPOD's software following the BODPOD's manual(12).
11. Before starting the actual measurements every participant was asked some background questions. These questions included the characteristics that were mentioned before: age, gender and ethnicity. Participants were asked to go to the toilet if they had not been recently.
12. Participants were asked to change to their swimsuit or similar clothing.
13. To calculate the BMI, length was measured on sight, as well as weight. Weight was determined with the scale that belongs to the BODPOD®, which is accurate to three decimals. The participants wore their swimsuit during the weighing.
14. The professional measured upper arm-, waist- and hip circumference with a Seca 201 tape-measure twice manually as described in 'Het Dietistisch Consult' by Becker-Woudstra et al(14).
15. The participant was asked to take place in the BODPOD®. The BODPOD® measurement took place. Lung volume was estimated by the BODPOD® as described in its manual(12).
16. The participant was scanned with the Kinect until a complete model was formed.
17. The professional adjusted the raw 3D-model. The 3D-model was used to measure volume and upper arm-, waist- and hip circumference.
18. The professional entered the results in SPSS. The variables that are set are: gender, length, weight, BMI, ethnicity and the different volume and anthropometric measurements as mentioned above.

The 3D scans were made with the software Artec Studio 9 (http://www.artec3d.com/software/artec-studio-10#compare-studios). This software was used to create and adjust the models as well as to do the measurements. When it was not possible to fill all the holes in Artec Studio, Netfabb was used to measure the volume of the model. Netfabb (http://www.netfabb.com/) is software used for 3D printing and is therefore able to fill all the holes.

The collected data was processed by using IBM SPSS Statistics 20. The variables gender, length, weight, BMI and ethnicity were descriptive variables. These variables were used to determine the heterogeneity of the population. The other variables, belonging to the measurements, were used to compare the different methods. For the tests that were done repeatedly, the average of the results was calculated.

The paired variables as viewed in table 1 were descriptively analysed with a Paired Samples T-test. Length was added to the variables used to compare the different measuring methods. The Intraclass Correlation Coefficient was calculated using an absolute agreement definition. The coefficients were assessed as described by Mukaka(15). The Bland Altman plot was used to show analogy between two numeral variables. This test displays whether the Kinect is sufficient to replace the BODPOD®. The Bland Altman test was repeated for every pair of variables.

Table 1 Variable pairs

Pair	*Variable 1*	*Variable 2*
1	MAN_arm	KINECT_arm
2	MAN_waist	KINECT_waist
3	MAN_hip	KINECT_hip
4	BODPOD_volume	KINECT_volume
5	Length	KINECT_length

Results

Subject characteristics are viewed in table 2.

Table 5 Subject characteristics

	Men (n=4)				*Women (n=21)*				*Total (n=25)*			
	min	max	mean		min	max	mean		min	max	mean	
Age (years)	20	43	27,5	±10,5	18	34	21,5	±3,6	18	43	22,4	±5,5
Length (m)	1,79	1,87	1,81	±0,03	1,57	1,83	1,69	±0,06	1,57	1,87	1,71	±0,07
Weight (kg)	74,4	91,2	79,4	±7,9	48,9	76,0	63,1	±7,6	48,9	91,2	65,7	±9,7
BMI (kg^2/m)	23,0	26,2	24,1	±1,5	18,4	25,2	22,1	±2,0	18,4	26,2	22,4	±2,0

The results from the manual anthropometries, BODPOD® volume measurements and Kinect-based measurements are viewed in table 3.

Table 3 Comparison of methods

	Manual or BODPOD®		*Kinect*		*Difference*		*Sig.*	*Correlation*
Circumferences (cm) n=24								
Upper arm	26,6	±2,1	30,1	±3,1	3,5	±2,2	<0,001	0,366
Waist	73,2	±6,8	80,2	±6,2	7,0	±1,3	<0,001	0,618
Hip	98,0	±5,9	104,6	±5,5	6,6	±2,0	<0,001	0,564
Volume (l) n=23	63,9	±9,6	76,6	±11,6	12,7	±3,1	<0,001	0,560
Length (m) n=25	1,71	±0,07	1,74	±0,07	0,03	±0,02	<0,001	0,902

Correlation

The correlation coefficient suggests a weak positive linear relationship in upper arm circumference, a moderate positive linear relationship in waist- and hip circumference and volume and a very strong positive linear relationship in length(15). These values suggest that the upper arm circumference is most influenced by noise, length on the other hand has nearly no influence of noise.

Bland Altman plots

The Bland-Altman plots reveal the bias of the Kinect based measurement. This is made visible in figure 1 to 5. The Bland Altman plots show the Kinect measured higher values for all participants than the comparison method's measurements. No proportional or fixed bias can be reliably interpreted from the figures, though the figures suggest possibility of a proportional bias with the trend of the difference being increased as mean circumference increases. The plots also show various degrees of deviation. Some body segments seem to be more influenced by overestimation than others.

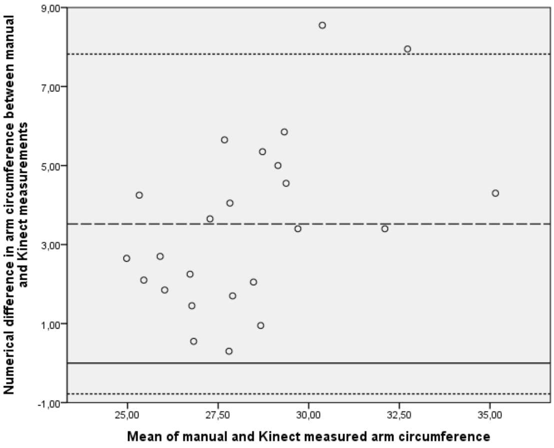

Figure 8 Bland Altman plot of the arm circumference. The X-axis contains the mean arm circumference (mean from the manual and Kinect measurement). The Y-axis contains the numerical difference in arm circumference between the manual and Kinect measurements. The upper and lower dashed lines are ±2SD-lines. The middle dashed line is the mean of Y. The solid line is the origin (0).

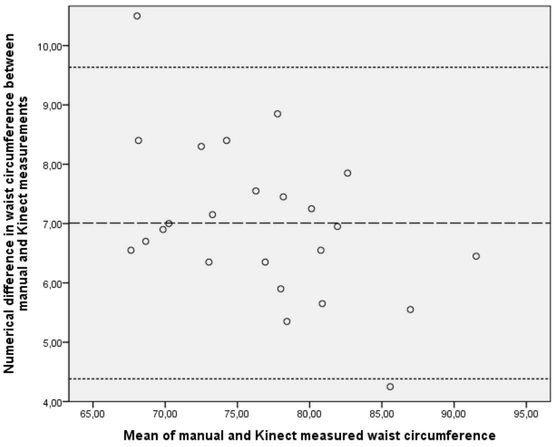

Figure 9 Bland Altman plot of the waist circumference. The X-axis contains the mean waist circumference (mean from the manual and Kinect measurement). The Y-axis contains the numerical difference in waist circumference between the manual and Kinect measurements. The upper and lower dashed lines are ±2SD-lines. The middle dashed line is the mean of Y.

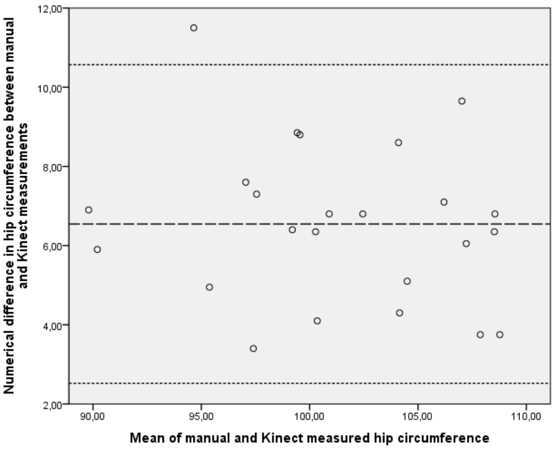

Figure 10 Bland Altman plot of the hip circumference. The X-axis contains the mean hip circumference (mean from the manual and Kinect measurement). The Y-axis contains the numerical difference in hip circumference between the manual and Kinect measurements. The upper and lower dashed lines are ±2SD-lines. The middle dashed line is the mean of Y.

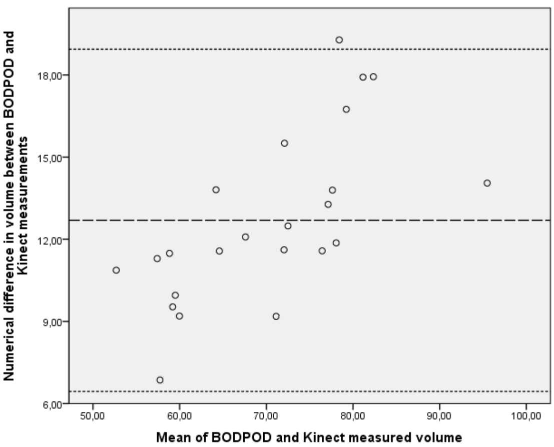

Figure 11 Bland Altman plot of the volume. The X-axis contains the mean volume (mean from the BODPOD and Kinect measurement). The Y-axis contains the numerical difference in volume between the BODPOD and Kinect measurements. The upper and lower dashed lines are ±2SD-lines. The middle dashed line is the mean of Y.

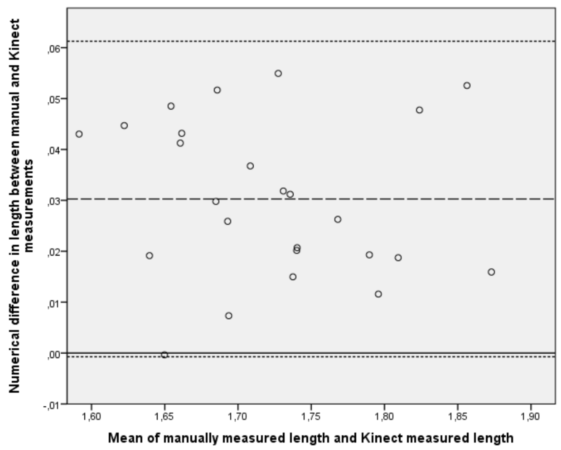

Figure 12 Bland Altman plot of the length. The X-axis contains the mean length (mean from the manual and Kinect measurement). The Y-axis contains the numerical difference in volume between the manual and Kinect measurements. The upper and lower dashed lines are ±2SD-lines. The middle dashed line is the mean of Y.The solid line is the origin at 0,00.

Conclusion

This was the first study to use Artec Studio 9 in combination with Microsoft's Kinect. This new method was compared to air displacement plethysmography and manual anthropometry. In conclusion, this study shows that the tested method is not applicable for health professionals. The Kinect combined with Artec is not a reliable and valid alternative for the comparison methods.

The literature suggests that the Kinect is a promising alternative for volume measurement, although calibration is a critical problem and the resolution of the cameras in the Kinect is poor. The results from the Kinect do not differ very much from reference laser systems.

This study found significant differences between the manual and BODPOD measurements and the Kinect measurements. The correlation coefficients suggest weak to almost perfect uphill linear relationships, but the scatterplots do not reflect that. Therefore the null hypotheses can be rejected.

Discussion

The significant difference between the methods could have had some reasons. First, the study did not correct for possible movement, for example breathing movements, by algorithm. The professional tried to correct movement when adjusting the models. This could have led to over- or under adjusting the models and therefor for under- or overestimation of the waist circumference and total volume.

Moreover, this study did not calibrate the Microsoft Kinect. The error that might have occurred by not calibrating the Kinect corresponds with the study by Khoshelham and Oude Elberink(16). Besides that, the method for adjusting the models slightly changed twice during the period of data collection. Unlike what the professional thought, this change in method did not decrease the percentage difference between the methods.

The professional noticed during the adjustment of the models that the arms and legs were a crucial part in creating a proper model. When making the model watertight for volume measurement, it seemed that the lower legs lacked detail and in some cases the software cut them off to achieve water tightness. In other cases, where the inside of the limbs were not scanned completely, the software filled them in itself. This led to inaccurate estimations, resulting in web-like connections between the arms and torso and between the legs. This might have led to overestimation of the volume and a decrease in accuracy of the upper arm circumference measurement.

Furthermore, not all subjects followed the quite strict body clothing protocol that should be used for the BODPOD. This could have had influences as described by Fields et al. Their study, focussing on the influence of body clothing, concluded that tight fitting one piece swimsuits gives most accurate results when using the BODPOD. Different clothing translates to a difference of fat mass up to more than five percent(17).

Although the population consisted solely of young Caucasians with a (fairly) healthy weight, it is plausible that the results of this study are generalizable for all people. This is likely because the population had a fairly easy body shape for scanning. Daniell et al describe that the eight different segments of the body they studied show different increasing patterns with increasing weight(18). This might have influence on the overestimation of the proposed method. That suggests that the deviation between the methods should be less for people with a fairly easy body shape. Since there were no overweight participants, it is only likely to think that the deviation is even greater for them.

The landmarks to measure the circumferences were determined based on visual characteristics of the subjects. A recommendation would be to retest with the use of software or algorithms that are able to locate these landmarks, for example the algorithm developed by Ben Azouz et al(19). This would decrease the chance of incorrect measurements. Since the professional assessed all participants similarly, it is not likely that this would have influenced the results in the present study so much that the outcome would be different.

When comparing to the found literature, one of the main differences is the software this study used. Therefore a recommendation would be to retest the procedure with different software, for example the SkanLab as described by Buffa et al(20). Furthermore, it would be recommendable to test for reliability of the proposed method. Though the proposed method is not valid enough to be applicable for health professionals, it could be of great use in the future. Further investigation should reveal this.

Finding a cheap, valid, reliable alternative for the BODPOD® and manual anthropometry would give more health professionals access to a device for determining body composition and body circumferences. This would make it easier to determine health risks and it would help health professionals to adapt treatment to individual needs.

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Appendix 2. 3D-scanning manual

For making 3D models of human bodies to measure body volume and upper arm-, waist- and hip circumference, we use a Microsoft Kinect and Artec Studio 9 software. Conditions for a successful 3D-scan:

- Use a room with a free space at least 220 cm in diameter. You have to walk in a circle around the subject, so make sure that there is possibility to.
- Because of the circle you will have to walk around the subject, make sure the extension cords you'll need to use are long enough. Ideally you place the extension cord in the circle before scanning, so you'll only have to follow the cord back.
- Make sure that the subject is standing in a position he/she can maintain for a couple of minutes.

Scanning

The first step is to start the software (Artec Studio, http://www.artec3d.com/software/artec-studio) and make sure that the 3D scanner is ready to use. When Artec Studio is ready, make sure to save the project in a recognizable way. Click the 'SCAN'-button in the upper left corner.

Make sure that Realtime Fusion is switched on and Delay start is set to 1 second. The scanning speed should be set at the fifth click from the left. Click preview. The scanner is now ready to use.

To make a useable model, it is important that the subject is standing in the correct position. The subject should stand like the pictures beneath. Picture A shows the ideal position, but since it is hard to maintain that position for a couple of minutes, picture B is acceptable too. It is extremely important that the arms don't touch the torso, as well as the upper legs shouldn't touch.

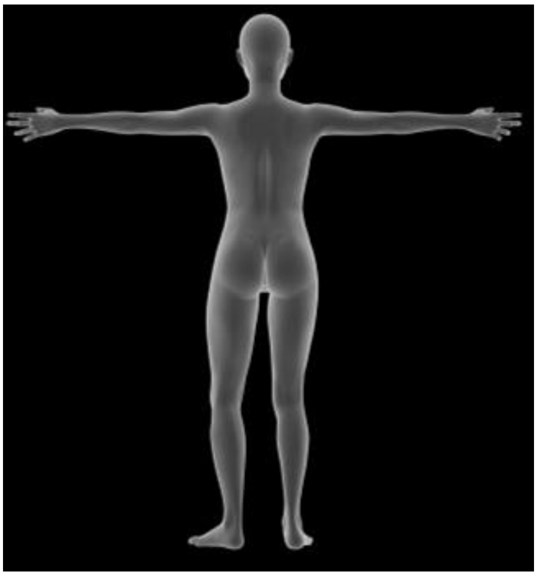


Figure A. Ideal position

Figure B. Acceptable position

The Kinect scanner has a depth range between 400 and 1600 mm to the object, so make sure that you don't get too close to or too far away from the object. Try to keep the blue peak in the middle of the green girder. This needs some practising. When the subject is positioned correctly, click record.

When recording, it is important to cover the whole subject with the 3D scanner. The Realtime Fusion will show the model you are making instantly. This way, you can see what parts are missing and have to be (re)scanned. Only scan what you need and try to scan not too much of the surroundings.

Moving the 3D scanner too fast will freeze the image and this means you will have to start over. Moving the 3D scanner too slowly will make the file unnecessarily big and hard to adjust. Ideal speed is about 4-5 frames per second. This needs some practising too. One 360° circle around the subject should be enough. Make sure that there are no parts missing, like the part under the chin and the top of the head. The bottom part of the feet cannot be scanned, but that is no problem.

Making the model useable

After scanning the subject, the model has to be cleaned, aligned and compressed.

First clean the surroundings roughly if necessary. Objects that are not in contact with the subject can be removed.

Secondly, the model has to be optimized. Select the 'Tools'-tab for this. You could run the tool automatically, but we prefer to run the tools one by one. The mode should be set to manual. The following steps have to be taken:

1. Global registration: with this tool the software optimizes its image of the subject.
2. Outliers removal: with this tool the software removes the surroundings that are no longer attached to the main object but which you might have missed (partly).
3. Smooth fusion: with this tool the object will be made watertight. Make sure the fill_holes option is set to watertight.
4. Small objects filter: the small objects filter removes parts of the scan that were not integrated in the smooth fusion.
5. Hole filling: this tool fills most of the gaps. Max_hole_len should be set to 10000. The software is not very smart, so the holes will be filled as plain as possible. If you missed for example the top part of the head, it will be flat after filling the hole.

The bigger the file, the longer this takes.

Cleaning the scan

Before cleaning the scan, we're going to align the scan. This is done with the positioning tool under the 'editor'-tab. Make sure the Z is pointing upwards.

Check if no unnecessary parts are in your scan. This could be the ceiling or the floor, something that is near the subject or whatever there should not be in your model. Everything that does not belong in the scan, should be removed. Use the tab 'Editor' for this.

The 'Editor'-tab contains an eraser. We first use the 'remove plain selection' tool to get rid of the floor. After removing the floor we have to use the earlier mentioned 'hole filling' again.

After removing the floor we use 'eraser' and 'defeature brush' to clean up the model. The eraser is used for the parts that are not so close to the object we want to keep, the defeature brush is used for the parts that are close to the object. The defeature brush 'heals' the model instantly so no gaps remain if done right. If you accidentally select a part of the model you don't want to erase, click cancel and start again. Check with the 'Fit to View'-option in the top of the screen if you miss anything that falls outside the range of the image.

Measuring

Measuring circumferences in Artec Studio

For measuring circumferences and volume, the 'Measures'-tab is used. In the 'Measures'-tab you can choose 'sections'. Make sure you name the section in a recognizable way, for instance 'Waist'.

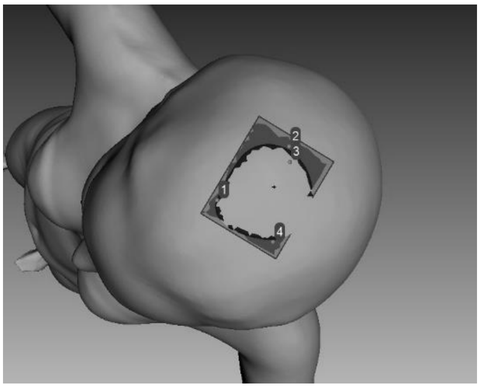
Then make sure that the 'not constrained'-option is on. With the left mouse button you can set points. When holding the left mouse button outside the model, you can turn it. Make sure you set enough points to make an exact section. That way, the circumference will be as close to manual measured circumferences as possible. When the software understands the circumference you want to measure, the circle around the model turns yellow. Click 'create section'.

In the information grid that appears, the contour is measured and the data will be shown. The information you want to know is the 'closed contour perimeter, mm'.

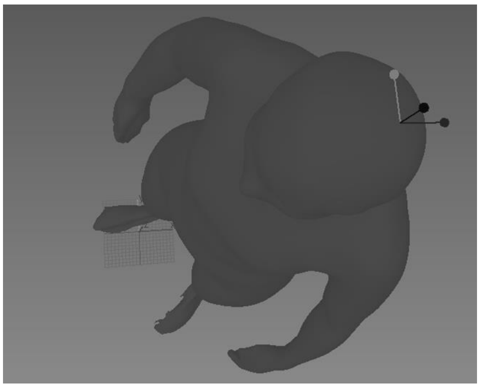
Measuring volumes in Artec Studio

Measuring volumes is similar to measuring circumferences. Select the 'measures'-tab and choose sections.

Turn the model to top view, so you see it from above. Select a couple of points on top of the head and make sure that the red selection is not in between this points, but around it, like in the image below.



Now click change position. First you use the translate-tab. Drag the Z-line to a bit above the model. Then click on the scale-tab and drag the arrows until the whole model is shown as in the image below. Click apply.



The information should now contain mesh volume in mm^3. This is the same as in decilitres, which is the same as 0,1 litre.

Appendix 3. Levels of evidence of the found literature in the literature search

Author	*Year*	*Study type*	*Level of evidence*	*Published in/at*	*Comments*
Dellen & Rojas	2013	Non-comparative study	C	Proceedings of the 16th Catalan Conference on Artificial Intelligence	Focussed on household objects
Khoshelham & Oude Elberink	2012	Non-comparative study	C	Sensors	Focussed on calibration of Kinect-like 3D scanners
Wan et al	2013	Non-comparative study	C	International Conference on MEC	Focussed on scanning mannequins
Clarkson et al	2014	Comparative study	B	Computer Vision – ECCV 2014 Workshops	Focussed on scanning living participants comparing with manual measurement
Weiss et al	2011	Comparative study	B	Proceedings of the 2011 International Conference on Computer Vision	Compared a single, inexpensive 3D scanner with a system based on multiple calibrated cameras and structured light sources
Menna et al	2011	Non-comparative study	C	Proceedings of SPIE	Report on the investigation of the Kinect sensors
Tong et al	2012	Non-comparative study	C	IEEE Transactions on Visualization and Computer Graphics	Focussed on qualities of the Kinect
Clarkson et al	2012	Comparative study	B	3rd International Conference on 3D Body Scanning Technologies Conference Paper	Compared the Kinect 3D scanner to the gold standard laser scanner
Soileau et al	2015	Comparative study	B	European Journal of Clinical Nutrition	Compared a Kinect-based 3D imaging method to a reference laser imaging system

Appendix 4. Background questions and measurement form

Number		
Gender		
Date of birth		
Length (m)		
Weight (kg)		
Ethnic background		
	Measurement 1	Measurement 2
Upper arm circumference (cm)		
Waist circumference (cm)		
Hip circumference (cm)		
Bodpod (litre)		
Kinect upper arm circumference (cm)		
Kinect waist circumference (cm)		
Kinect hip circumference (cm)		
Kinect volume (litre)		

Appendix 5. SPSS-variables

Name	*Label*	*Values*	*Missing*	*Measure*
Number	Number of participant			Scale
Age	Age of participant			Scale
Gender	Gender of participant	1 = man 2 = woman		Nominal
Length	Length of participant in m measured manually			Scale
Weight	Weight of participant in kg measured by BODPOD			Scale
BMI	BMI in kg/m2			Scale
Ethnicity	Ethnic background (race) of participant	1 = White/Caucasian 2 = Black/African/Caribbean 3 = Asian/Pacific Islander 4 = Hispanic/Latino 5 = Other 6 = Mixed		Nominal
MAN_arm	Average of manually measured upperarm circumferences		-1,0	Scale
MAN_waist	Mean of manually measured waist circumferences		-1,0	Scale
MAN_hip	Mean of manually measured hip circumferences		-1,0	Scale
BODPOD_volume	BODPOD measured volume		-1,000	Scale
KINECT_arm	Mean of Kinect measured upperarm circumferences		-1,0	Scale
KINECT_waist	Mean of Kinect measured waist circumferences		-1,0	Scale
KINECT_hip	Mean of Kinect measured hip circumferences		-1,0	Scale
KINECT_volume	Kinect measured volume		-1,000	Scale
MAN_arm1	First manual measurement upperarm circumference		-1,0	Scale
MAN_arm2	Second manual measurement upperarm circumference		-1,0	Scale
MAN_waist1	First manual measurement waist circumference		-1,0	Scale
MAN_waist2	Second manual measurement waist circumference		-1,0	Scale
MAN_hip1	First manual measurement hip circumference		-1,0	Scale
MAN_hip2	Second manual measurement hip circumference		-1,0	Scale
KINECT_arm1	First Kinect measurement upperarm circumference		-1,0	Scale
KINECT_arm2	Second Kinect measurement upperarm circumference		-1,0	Scale
KINECT_waist1	First Kinect measurement waist circumference		-1,0	Scale
KINECT_waist2	Second Kinect measurement waist circumference		-1,0	Scale
KINECT_hip1	First Kinect measurement hip circumference		-1,0	Scale
KINECT_hip2	Second Kinect measurement hip circumference		-1,0	Scale

DIF_volume	Percentage difference in volume between BODPOD and Kinect measurements		Scale
DIF_arm	Percentage difference in upperarm circumference between manual and Kinect measurements		Scale
DIF_waist	Percentage difference in waist circumference between manual and Kinect measurements		Scale
DIF_hip	Percentage difference in hip circumference between manual and Kinect measurements		Scale
NUMDIF_volume	Numerical difference in volume between BODPOD and Kinect measurements		Scale
NUMDIF_arm	Numerical difference in upperarm circumference between manual and Kinect measurements		Scale
NUMDIF_waist	Numerical difference in waist circumference between manual and Kinect measurements		Scale
NUMDIF_hip	Numerical difference in hip circumference between manual and Kinect measurements		Scale
GEM_bpkin_vol	Mean of BODPOD and Kinect measured volume		Scale
GEM_mankin_arm	Mean of manual and Kinect measured upperarm circumference		Scale
GEM_mankin_waist	Mean of manual and Kinect measured waist circumference		Scale
GEM_mankin_hip	Mean of manual and Kinect measured hip circumference		Scale
KINECT_length1	First Kinect measured length in m		Scale
KINECT_length2	Second Kinect measured length in m		Scale
KINECT_length	Mean of Kinect measured lengths		Scale
GEM_mankin_length	Mean of manual and Kinect measured length		Scale
NUMDIF_length	Numerical difference in length between manual and Kinect measurements		Scale
PERDIF_length	Percentage difference in length between manual and Kinect measurements		Scale
SCANS_needed	Scans needed to create a proper model	-1	Scale