J Forensic Sci, November 2008, Vol. 53, No. 6
doi: 10.1111/j.1556-4029.2008.00874.x
Available online at: www.blackwell-synergy.com

Peter K. Larsen,[1] M.Sc.; Lone Hansen,[1,†] Ph.D.; Erik B. Simonsen,[2] Ph.D.; and Niels Lynnerup,[1] Ph.D.

Variability of Bodily Measures of Normally Dressed People Using PhotoModeler® Pro 5*

ABSTRACT: Photogrammetry is used in forensic science to help identify perpetrators from crime scenes by way of surveillance video, but the reproducibility of manually locating hidden body-points such as the joints remains to be established. In this study, we quantified the inter- and intra-observer variability of bodily measures of clothed individuals in two different poses and examined whether body segment lengths could be used to distinguish between people of similar stature. Stature was reproduced within ±1.5 cm in both the intra- and inter-observer study. Segment lengths were best reproduced when flexion in the joints was present in the intra-observer study, but only the length of the trunk could be used to distinguish between people of similar height. The reproducibility between the two poses was low. Other measures than stature should be used with caution and with the perpetrator and suspect in the same pose. Consistent guidelines for locating body-points should be developed.

KEYWORDS: forensic science, forensic anthropology, photogrammetry, reproducibility of results, body weights and measures

The robbery of a bank is a serious crime not least because some of the central victims, the bank personnel, often develop psychological problems resulting from the event. Video surveillance systems are used for prevention, or subsequently identification of the perpetrator; however, if the perpetrator is disguised, the surveillance system may be of little help in identification. To partly overcome this problem, photogrammetry has been used in forensic medicine since the 1970s (1). Photogrammetry enables the measurement of unknown values in two-dimensional space (2D) using known values within a single image (2,3). Another basic application of photogrammetry is measuring objects in three-dimensional space (3D) using photographs taken from different sides and angles. Jensen and Rudin (3) used a 2D method to measure the stature and several segment lengths in two different cases and found excellent agreement between perpetrator and suspect. Lynnerup and Vedel (2) used a 3D method in the investigation of a bank robbery where the perpetrator was recorded simultaneously from two different cameras and found good agreement in bodily measurements when comparing the perpetrator to the suspect.

Photogrammetry is extensively used in architecture. Based on images with high resolution it is possible to obtain the exact location of clearly defined points such as the corner of a building. However, very little is known about the accuracy of locating hidden body-points, e.g., the shoulder joint hidden behind several layers of clothing, in images obtained with low-resolution surveillance cameras.

[1]Laboratory of Biological Anthropology, Section of Forensic Pathology, Department of Forensic Medicine, Faculty of Health Sciences, University of Copenhagen, Blegdamsvej 3, Copenhagen DK-2200, Denmark.

[2]Department of Neuro Science and Pharmacology, Faculty of Health Sciences, University of Copenhagen, Blegdamsvej 3, Copenhagen DK-2200, Denmark.

*This work is based on a study first reported in the Proceedings of Spie: Larsen PK, Hansen L, Simonsen EB, and Lynnerup N. Variability of Bodily Measures of Normally Dressed People Using PhotoModeler® Pro. *Proc. Spie*. In: Beraldin J-A, Remondino F, Shortis MR, editors. Videometrics **IX** 2007 Jan 27, San Jose, CA: SPIE 2007 64910Z.

†Present address: Team Danmark, Broendby Stadion 20, Broendby DK-2605, Denmark.

Received 6 Oct 2007; and in revised form 13 Apr. 2008; accepted 13 Apr. 2008.

To summarize, use of photogrammetry in forensics fulfills three of the four guidelines in the Daubert Standard, a legal precedent set by the Supreme Court of the United States (4), for determining whether expert witnesses' testimony is admissible as evidence: (1) the testimony in court is based on an empirically used technique, (2) the technique has been published in peer-reviewed literature, and (3) it is generally accepted for use in forensic medicine. The last Daubert Guideline states that the reliability of the technique has been tested and potential error rates known. This guideline remains to be fulfilled because the reproducibility of locating body-points has not been adequately investigated.

In this study, we therefore (using the software package PhotoModeler® Pro 5) quantified the intra- and inter-observer variability of locating several body-points based on low-resolution images obtained from standard digital video cameras. Subsequently, we established the reproducibility of determining stature, other heights, and body segment lengths derived from the location of the body-points.

Methods

Image recording took place in a gait laboratory equipped with five wall-mounted digital cameras (720 × 576 pixels), each denoted as a camera station when used in PhotoModeler® Pro 5 (5). When a subject was placed in a given pose (see below), camera station 1 recorded the right side of the subject, camera station 2 the front/right side with an angle around 45°, camera station 3 the backside, camera station 4 the front, and camera station 5 the left side from a frontal angle about 10° (Fig. 1). Table 1 shows the height, distance, and angle from each camera station to the subject. Based on our work with forensic cases, surveillance cameras often capture perpetrators under such circumstances.

Three-Dimensional Model

The camera stations were calibrated in PhotoModeler® Pro 5 to determine characteristics of the lens, such as focal length and distortion, using a calibration sheet developed by Eos Systems Inc. for use with PhotoModeler® Pro 5. The camera stations were

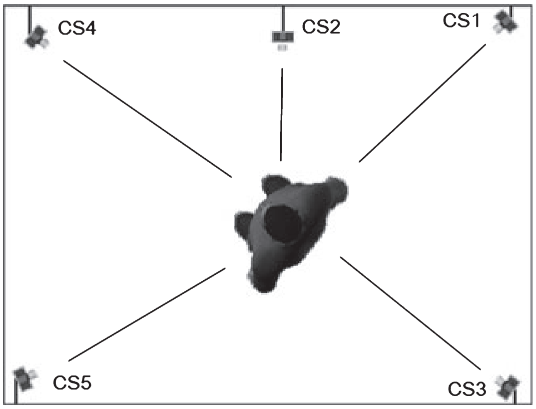

FIG. 1—*Placement of the camera stations as derived from PhotoModeler® Pro 5.*

TABLE 1—*Data for placement of the camera stations.*

CS	Height (m)	Distance (m)	Angle (°)
1	2.3	5.5	67.9
2	0.9	4.0	85.1
3	2.3	4.6	64.1
4	2.2	5.9	68.8
5	2.2	5.4	57.1

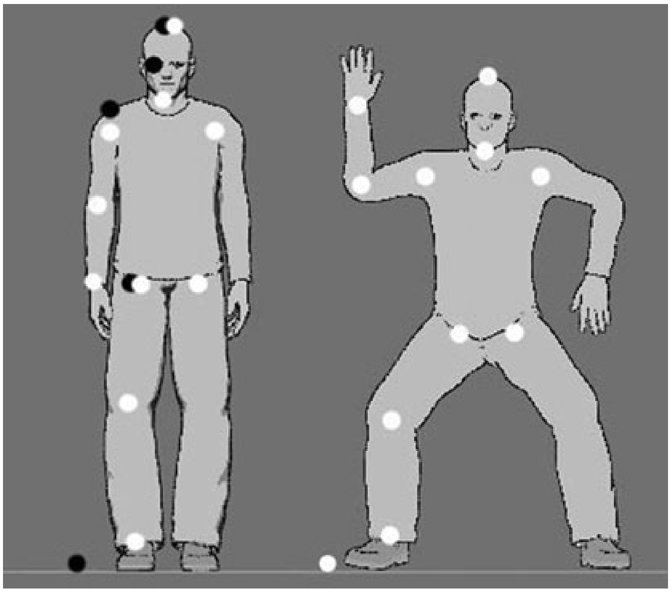

FIG. 2—*The two poses: pose 1 (left) was each subject's normal standing posture. In pose 2 (right), the subjects were instructed to stand with flexion in the joints of the extremities. The black dots represent the points used to calculate heights (the points at the apex, the eye, the acromion, the hip, and the reference marker on the floor). The white dots represent the points that were used for determining body segment lengths (apex, the chin, the shoulders; and the elbow, wrist, ankle, knee, and hip at the right extremities). The points at the apex and the hip for pose 1 were used for calculation of heights as well as segment lengths.*

orientated according to a Cartesian coordinate system by recordings of 46 markers covering most of each camera's view and each marker was identified from at least three camera stations. The orientation of the camera stations was accepted when the distance between straight lines projected from the position of each camera station to each marker was below 0.1 cm. PhotoModeler Pro 5 could then calculate the *x*, *y*, and *z* coordinates and construct a 3D model accurately. A known distance between two markers on the floor was used to scale the 3D model.

Subjects

Fifteen male subjects (students and staff at the Faculty of Health Sciences with mean stature: 181.7 cm, standard deviation (SD): 5.5 cm) were recruited to the inter-observer study. Each subject was recorded in two different poses (Fig. 2): each subject's normal standing posture (pose 1) and a posture with marked flexion in the joints of the extremities (pose 2). The subjects were recorded in their everyday clothing which included T-shirt/sweatshirt/shirt, loose-fitting trousers, and shoes.

One frame for each pose and subject was grabbed from each camera station and loaded into the 3D model.

Points and Guidelines for Plotting Points

Thirteen points (12 body-points and a reference marker on the floor) and 10 points (nine body-points and a reference marker on the floor) were chosen for plotting for poses 1 and 2, respectively (Fig. 2). The body-points were set at anatomical landmarks or in the joint centers. The following guidelines were used for plotting these points: the point on top of the head was placed at the apex of the cranium (apex), the eye-point was set at the lateral corner of the eye, and the shoulder height was obtained using a marker on the acromion. Finally, the joint centers of the shoulders, hips, knee, and ankle were identified by help of pictures showing the placement of each point relative to the body surface (6,7).

The reference marker plotted on the floor was used to establish the degree of precision of a clearly defined object and to find the coordinates of the floor so heights in reference to the floor could be calculated.

When plotting, the location of a body-point was accepted when the largest distance between straight lines projected from each camera station used to locate the point did not exceed 0.5 cm.

Determination of Heights and Segment Lengths

Five points for pose 1 (black dots in Fig. 2) were used to determine heights relative to the floor using ordinary vector calculation. Only the vertical coordinates from the 3D location were used for this purpose. The stature was determined by adding 1.1 cm to the vertical distance between the apex and the point on the floor (the distance the center of the marker on the floor was placed above ground). Heights were only calculated for pose 1 since e.g., stature would give no meaning with the legs flexed. A reference measurement of stature was obtained with a Seca 225 stadiometer (Seca Ltd., West Midlands, UK).

Ten and 11 points for poses 1 and 2 (shown in white in Fig. 2), respectively, were used to calculate body segment lengths (Table 2) based on their 3D-coordinates. The length of the trunk was calculated as the distance between the midpoint of a vector between the two hip-points and the midpoint of a vector between the two shoulder points.

The stature was determined piecemeal in the inter-observer study by adding the height from floor to ankle to the segment lengths of the calf, thigh, trunk, and neck–head segment (black arrows in the right side of Fig. 3). The head–neck segment was calculated as the distance from the midpoint of the vector between the shoulder joints to the point at the apex.

TABLE 2—*Reproducibility of heights to floor.*

	Intra-observer study		Inter-observer study		Ref.
Heights to floor	Mdif* (cm)	(LPL to UPL)†	Mdif* (cm)	(LPL to UPL)†	PL‡ (cm)
Stature	0.0	(−1.0 to 1.0)	−0.3	(−1.5 to 0.9)	
Eye	0.0	(−1.2 to 1.1)	−0.5	(−1.3 to 0.4)	
Acromion	−0.3	(−2.4 to 1.8)	−0.9	(−2.2 to 0.4)	
Hip joint	−1.3	(−2.8 to 5.4)	−3.2	(−9.4 to 3.1)	6.1

*The mean difference between the first and second determination of the measure of each subject.
†95% lower and upper prediction limits.
‡Prediction limits for normal deviation between men of similar stature.

Intra- and Inter-Observer Study

Two different observers (LH and PKL) established the 3D position of all points for each of the 15 subjects to determine the inter-observer variability. One of the observers (PKL) repeated the process 2 months later to establish the intra-observer variability based on eight of the subjects. These eight subjects were selected so the stature of this group and the original group were evenly distributed.

Reference Group

To examine whether any of the segment lengths could be used to distinguish between people of similar stature, the normal variation in body segment lengths was determined based on 39 men with the same stature (177 ± 1 cm). Anthropometric measurements of these men were obtained from the National Institute of Occupational Health (NIOH) in Denmark (8). The SD × 2 of these measurements was used as the prediction limits of how much a given body segment length may deviate between men of the same stature. If the 95% upper prediction limit (UPL) of a given body segment length found in this study was less than half the variation in the reference group, this segment length was defined as a possible contributor to distinguish between men of similar stature.

The height of the head was not established in the NIOH-study. Instead, prediction limits were established using the SD × 2 of the head height in a U.S. army survey (9) based on 1776 subjects of different heights and different ethnical heritage.

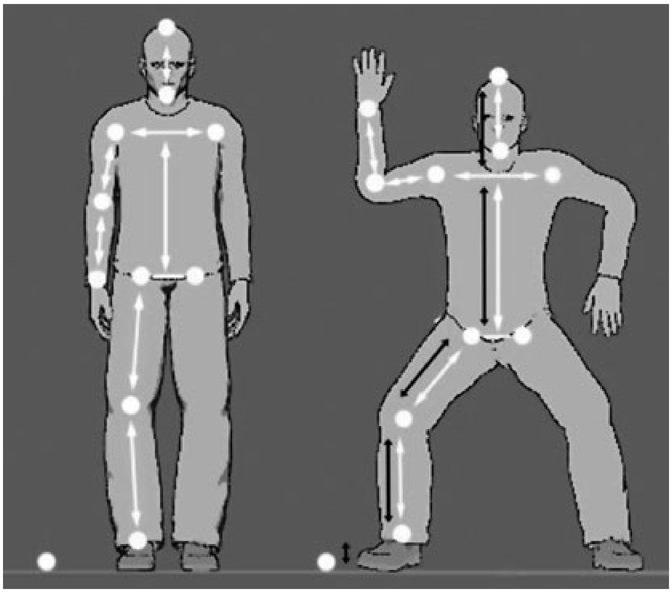

FIG. 3—*Illustration of the body segment lengths presented in Tables 4, 5, and 6.*

Calculations and Statistics

Body segment lengths were calculated with ordinary vector calculation using the 3D-coordinates of the two points defining each segment. Heights to floor were calculated using only the vertical coordinate of the points defining the height. The difference between the first and second determination of each bodily measure in the same pose was calculated for each subject and the mean difference for all subjects was found. The reproducibility of a given measure was expressed as the 95% lower prediction limit (LPL) and UPL calculated as:

$$\mathrm{LPL/UPL} = \mathrm{mdif} \pm \ \mathrm{SD} \ \times t(0.975[n-1]) \times \text{square root}(1 + 1/n)$$

where mdif = mean difference between the first and second determination of a given measure of each subject, SD = standard deviation of the differences between first and second determination of the measure, and t(0.975[$n-1$]) was the 0.975 fractile in a t-distribution with $n-1$ degrees of freedom (10).

The prediction limits represent the largest expected difference (worst-case scenario) between two new determinations on a new subject. A further new difference is introduced between the two new determinations on the new subject. The last part of the formula (square root [1 + 1/n]) includes this added difference.

The degree of measuring agreement between poses 1 and 2 was found by calculating the SD of the differences between the mean of the two observers' determinations of each pose (SD mean). This SD could not be used directly to calculate the LPL/UPL with the above formula, because some of the error of the repeated measurement of each pose has been removed by using the mean. This is corrected by finding the SD of the differences between the two observers' determination of pose 1 (SD p1), and the two observers' determination of pose 2 (SD p2) (11). These standard differences are combined to a corrected SD:

$$\mathrm{SD, corrected}\ (1) = \mathrm{sqroot}\ (\mathrm{SD\ mean}^2 + 1/4 \times \mathrm{SD\ p1}^2 + 1/4 \times \mathrm{SD\ p2}^2)$$

.

When establishing the measurement agreement between stature obtained by photogrammetry and reference height measured with stadiometer, the SD was only corrected with the SD of the differences between the two determinations of the stature obtained by photogrammetry (SD phot.) because the reference height was not a repeated measurement:

$$\mathrm{SD, corrected}\ (2) = \mathrm{sqroot}\ (\mathrm{SD\ mean}^2 + 1/4 \times \mathrm{SD\ phot.}^2)$$

These corrected SDs were then used in the previous described formula.

The computer program MS Excel (12) was used for all calculations.

Results

Reproducibility of Points

Figure 4 shows box-whisker plots of the differences in placement of the points used to determine heights (only the vertical coordinate of the apex, eye, acromion and the hip—black dots in Fig. 2). It can be seen that the floor-, apex-, and eye-point could be replaced within 1.5 cm and the acromion-point within 2.5 cm in both the intra- and inter-observer study. The point at the hip joint was more difficult to reproduce resulting in higher variability, especially in the inter-observer study where the location of the point deviated up to 7–8 cm.

The differences in placement of the points used to determine segment lengths (white points in Fig. 2) are shown in Fig. 5. Only the reference-point on the floor could be reproduced as good in 3D as in the vertical direction. All body-points show larger deviations and variability, and the points generally have lower reproducibility in the inter-observer study than the intra-observer study. The points at the hip and knee have the lowest reproducibility, especially in pose 1 where no flexion is present in the joints. Flexion only seems to result in markedly better reproducibility in the ankle and knee joint in the intra-observer study.

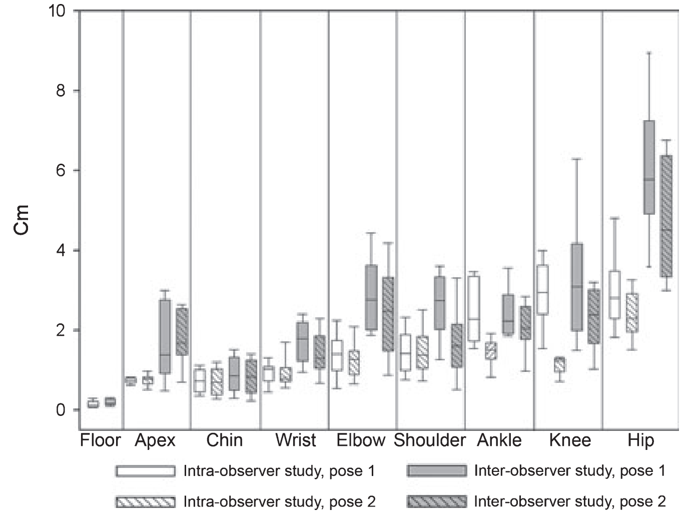

FIG. 5—*Box-plots of the differences between the first and second determination of points used to determine segment lengths. The whiskers show the 10th and 90th percentile. Outliers are omitted.*

Reproducibility of Heights and Body Segment Lengths

The prediction limits for heights calculated on the basis of the points in Fig. 4 are shown in Table 2. The first three rows show that the determined stature and the height from the eye to floor could be reproduced in both the intra- and inter-observer study with ±1.5 cm and the height from the acromion to floor could be reproduced with about ±2.5 cm. The prediction limits for normal variation in a given segment length calculated on the basis of the reference group (from the NIOH-study) are shown in the last column. The height from the hip-point to the floor had an LPL/UPL of the same magnitude as the prediction limit derived from the reference group in both the intra- and inter-observer study. The NIOH-study did not contain data of the height from eye or acromion to floor. The difference between the LPL and UPL for the point at the hip in the inter-observer study indicates a systematic difference in the observers' perception of the location of the hip joint.

Table 3 shows the relationship between the determined stature and the reference stature obtained with a stadiometer. The prediction limits show that the stature measured by photogrammetry for a single new subject can be expected to be around 1.5 cm below to 2.5 cm above the stature measured with a stadiometer in both the intra- and the inter-observer study.

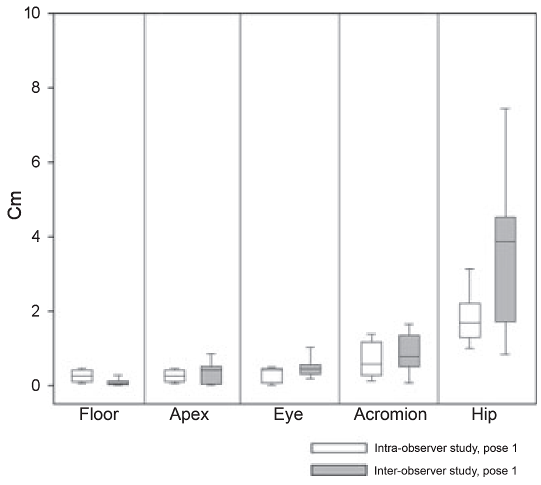

FIG. 4—*Box-plots of the differences between the first and second determination of points used to determine heights to floor. The whiskers show the 10th and 90th percentile. Outliers are omitted.*

The prediction limits for body segment lengths in the intra-observer study are shown in Table 4. The height of the head had the lowest LPL/UPL and therefore the highest degree of reproducibility in both poses. The last column shows that the normal variation of the head height is within ±1.8 cm based on a heterogeneous U.S. male population (9). The prediction limits for measured differences of the head height were in pose 1 less than half the predicted normal variation and are therefore a possible contributor to distinguish between people of different heights. The trunk was identified as a possible contributor to distinguish between people of similar stature based on the NIOH-study in pose 2. The lower arm and the measures of the leg seem to be markedly better reproduced in pose 2 compared with pose 1 (marked with bold face). These measures could nearly fulfill the criteria for being a possible contributor to distinguish between men of similar stature.

Table 5 shows the reproducibility of the segment lengths in the inter-observer study. All segment lengths had lower reproducibility limits than in the intra-observer study and no measures could contribute to distinguish between people of similar stature. However, the calf and the thigh seem to be markedly better reproduced in pose 1 than in pose 2 while the lower + upper arm showed the opposite picture (marked with bold face). The prediction limits for the trunk, shoulder width, lower arm, thigh and calf + thigh in pose 1 and for the lower arm and lower + upper arm in pose 2 seem

TABLE 3—*Measuring agreement between statures measured with statometer and determined by photogrammetry, respectively.*

	Intra-observer study		Inter-observer study	
	Mdif* (cm)	(LPL to UPL)† (cm)	Mdif* (cm)	(LPL to UPL)† (cm)
Stature versus stadiometer height	0.5	(−1.4 to 2.5)	0.8	(−1.0 to 2.6)

*The mean difference between the first and second determination of the measure of each subject.

†95% lower and upper prediction limits.

Positive values mean that the stature obtained by photogrammetry is higher than the stature measured with stadiometer.

TABLE 4—*Reproducibility of body segment lengths, intra-observer study.*

	Pose 1		Pose 2		Ref.
	Mdif* (cm)	(LPL to UPL)† (cm)	Mdif* (cm)	(LPL to UPL)† (cm)	PL‡ (cm)
Head height	0.0	(−0.6 to 0.6)§	0.2	(−1.2 to 1.6)	1.8¶
Trunk	−1.4	(−5.9 to 3.2)	0.2	(−2.1 to 2.4)§	5.5
Shoulder width	−0.7	(−4.5 to 3.0)	0.5	(−2.9 to 3.9)	3.3
Lower arm	0.2	(−4.4 to 4.7)	−0.2	**(−2.1 to 1.8)**	4.1
Upper arm	−0.2	(−4.6 to 4.2)	−0.5	(−3.7 to 2.7)	4.0
Lower + upper arm	−0.1	(−3.5 to 3.4)	−0.7	(−3.8 to 2.5)	5.5
Calf	−1.5	(−8.9 to 5.8)	0.2	**(−2.0 to 2.5)**	4.1
Thigh	−1.3	(−4.8 to 7.3)	−0.4	**(−3.6 to 2.8)**	7.0
Calf + thigh	−0.3	(−6.6 to 6.0)	−0.1	**(−3.2 to 3.0)**	6.1
Stature determined piecemeal			0.2	(−2.6 to 2.9)	

Values in bold: The measure seems to be better reproduced in this pose.
*The mean difference between the first and second determination of the measure of each subject.
†95% lower and upper prediction limits.
‡Prediction limits for normal deviation between men of similar stature.
§Prediction limits are less than half the variation in the reference group and the segment length may therefore contribute to distinguish between subjects of similar stature based on the NIOH-study.
¶Prediction limits for normal deviation between men from the U.S. army.

TABLE 5—*Reproducibility of body segment lengths, inter-observer study.*

	Pose 1		Pose 2		Ref.
	Mdif* (cm)	(LPL to UPL)† (cm)	Mdif* (cm)	(LPL to UPL)† (cm)	PL‡ (cm)
Head height	−0.2	(−1.9 to 1.5)	−0.3	(−2.4 to 1.9)	1.8§
Trunk	3.6	(−1.8 to 9.0)	2.2	(−4.6 to 9.0)	5.5
Shoulder width	−3.2	(−8.9 to 2.5)	−0.3	(−5.5 to 5.0)	3.3
Lower arm	−2.5	(−6.2 to 1.2)	−2.3	(−5.1 to 0.5)	4.1
Upper arm	1.4	(−2.9 to 5.8)	−0.4	(−5.2 to 4.3)	4.0
Lower + upper arm	−1.0	**(−4.4 to 2.3)**	−2.7	(−8.8 to 3.3)	5.5
Calf	0.3	(−5.0 to 5.5)	−0.4	**(−3.7 to 3.0)**	4.1
Thigh	−5.0	(−14.5 to 4.5)	−1.8	**(−8.8 to 5.1)**	7.0
Calf + thigh	−4.7	(−11.9 to 2.4)	−2.2	(−9.8 to 5.4)	6.1
Stature determined piecemeal			−0.3	(−4.3 to 3.7)	

Values in bold: The measure seems to be better reproduced in this pose.
*The mean difference between the first and second determination of the measure of each subject.
†95% lower and upper prediction limits.
‡Prediction limits for normal deviation between men of similar stature based on the NIOH-study.
§Prediction limits for normal deviation between men from the U.S. army.

unequal with higher mean differences suggesting a systematic difference between the two observers.

Pose 1 Compared with Pose 2

Table 6 shows the measuring agreement between the two poses. The mean differences were of the same magnitude as in the inter-observer study and all body segment lengths had prediction limits greater than the NIOH-values.

The upper arm and lower + upper arm had a tendency to be longer in pose 1 than pose 2, while the determinations of the shoulder width, the calf, and the calf + thigh showed the opposite. The stature obtained piecemeal in pose 2 also showed a tendency to larger values than the stature derived from pose 1 with a remarkably reduced reproducibility compared to the reproducibility of determining the stature in pose 1 (Table 6).

TABLE 6—*Measuring agreement between segment lengths determined from poses 1 and 2, respectively.*

	Pose 1 versus Pose 2		Ref.
	Mdif* (cm)	(LPL to UPL)† (cm)	PL‡ (cm)
Head height	−0.3	(−2.9 to 2.3)	1.8§
Trunk	1.5	(−6.3 to 9.4)	5.5
Shoulder width	−4.7¶	(−11.6 to 2.3)	3.3
Lower arm	1.1	(−2.1 to 4.3)	4.1
Upper arm	3.7¶	(−2.3 to 9.6)	4.0
Lower arm + upper arm	4.8¶	(−0.7 to 8.9)	5.5
Calf	−3.8¶	(−11.3 to 3.7)	4.1
Thigh	1.5	(−6.8 to 9.8)	7.0
Calf + thigh	−2.3¶	(−11.2 to 6.7)	6.1
Stature versus piecemeal determination	1.2	(−3.9 to 6.3)	

*The mean difference between the first and second determination of each measure of each subject.
†95% lower and upper prediction limits.
‡Prediction limits for normal deviation between men of similar stature based on the NIOH-study.
§Prediction limits for normal deviation between men from the U.S. army.
¶Indication of systematic difference between the determinations of the segment length between the two poses. Negative values indicate that the segment lengths are estimated to be longer in pose 2 than in pose 1.

Discussion

In this study, we used recordings from five low-resolution cameras as the basis of 3D photogrammetry using the software PhotoModeler® Pro 5.

Two studies (2,3) have shown excellent agreement for several body segment lengths and height measurements between perpetrator and suspect in case studies. However, to our knowledge, no one has examined the reproducibility of how body-points are placed or the length of other bodily measures than the stature.

This study is based on a relatively small number of subjects, especially in the intra-observer study. However, the SD and hence the prediction limits, which we report in this study, are less influenced by the number of subjects (10) so the limited number of subjects is a minor problem.

We found that the position of a clearly defined reference marker on the floor could be reproduced within 0.5 cm. The same degree of accuracy has previously been reported with a similar method (13).

In this study, all body-points were more difficult to reproduce than the reference point. The points, which were located on the surface of the body (chin, eye, and acromion), were the best-reproduced points and the reproducibility was equally good in the intra- and inter-observer study.

When the points were placed in the joints hidden by clothes, the reproducibility generally decreased, especially in the inter-observer study. We found highest variability for the points at the hip joint and the straight knee joint in pose 1 where the joint position was very difficult to locate because of the loose-fitting trousers in this pose. We therefore expect that the reproducibility of the points not covered by clothes at the head would decrease if a perpetrator covered the head. In this case, we propose to use the most pronounced parts of the face as measurement points, e.g., the eyes if they can be seen through holes in a balaclava or a possible prominent nose seen in profile.

We expected that the reproducibility of locating the joints of the extremities would augment with the flexed joints in pose 2, but only the location of the ankle joint in the intra-observer study and the knee joint in both studies seemed to have markedly better reproducibility in this situation. However, the wrist joint was recognizable in both poses and the elbow joint was slightly flexed in all the subjects in pose 1 so the extra flexion in pose 2 did not enhance the process of location of these two joints. It was surprising that the variability of the hip joint did not decrease with flexion. We hypothesize that it was partly caused by the combined abduction and flexion of the hip in pose 2. It was our experience that the abduction made it more difficult to locate the joint. Conclusively, we suggest that location of the elbow joint and the joint of the lower extremities should be performed on images with flexed joints, if possible, to enhance reproducibility.

Based on the best reproducible surface-points, we could, independent of observer, reproduce the stature and eye-floor height within ±1.5 cm and the acromion-floor height within ±2.5 cm. Klasén and Fahlander (14) and Criminisi et al. (13) could establish the stature of a person within the same margin to "the true value." Nonetheless, neither of these studies discussed how they found a person's "true stature."

When we compared the stature determined photometrically to measurement with the stadiometer, the prediction limits were wider with a tendency towards higher values for the stature obtained by photogrammetry. This is surprising because the subjects were instructed to stand with their legs, back, and neck in straight position when measured with the stadiometer, as opposed to each subject's normal and more relaxed standing position used for the photogrammetric determination of stature. We therefore expected that the subjects would actually stand in a higher pose during the stadiometer measurement. The tendency to overestimate the stature obtained by photogrammetry may have been caused by a too high placement of the point at the apex because of the hair. This source of bias was eliminated when measuring with the stadiometer by placing the measuring slide firmly at the apex. We therefore suggest that measurements of both perpetrator and suspect should be performed with photogrammetry to avoid bias caused by difference in measuring technique. This would also give the possibility to explain differences in stature caused by differences in poses as Criminisi et al. (13) did.

We could reproduce the stature to within about 1.5 cm, so other bodily measures may only be relevant if they provide additional information. Therefore, the reproducibility of other bodily measures has to be good enough to detect differences within normal variation in body segment lengths between subjects of similar stature.

We found that only the trunk in pose 2 could be used to give additional information in the intra-observer study. However, with the joint of the extremities flexed in pose 2, several other body segment lengths seemed to be better reproduced than in pose 1 and they could nearly fulfill the criteria for being a contributor to distinguish between men of similar stature.

The height of the head was determined on the basis of some of the most reproducible points and showed the lowest LPL/UPL in this study. Still, it was only in one of the poses in the intra-observer study that this measure could be used to distinguish between men of different heights. This indicates that even though the points at the head are reproducible, the normal variation in measures of the head is so small that photogrammetric measurements are too imprecise to detect the differences.

In the inter-observer study, no body segment lengths were of such reproducibility that they could detect differences within men of similar stature.

This poses a problem because use of photogrammetry in forensic medicine must be independent of the observer. However, the better reproducibility in the intra-observer study suggests that it is possible to improve the inter-observer variability if better guidelines for plotting and identifying points are developed. Furthermore, if two different observers had to determine body segment length of perpetrator and suspect, respectively, they would presumably come to similar conclusions because this would be two independent intra-observer situations.

We believed that piecemeal determination of the stature and the length of the arm (lower + upper arm) and leg (calf + thigh) would result in better reproducibility, than determining each segment length. A deviation in locating e.g., the elbow joint could simply result in measuring e.g., a shorter upper arm and longer lower arm while the length of the upper + lower arm would remain the same. This hypothesis was not confirmed. The arm and leg determined piecemeal had the same reproducibility as the arm and leg segment with the lowest reproducibility. Determining the stature piecemeal resulted in the same degree of reproducibility as all the segment lengths in average (± 4.3 cm). It is considerably lower than the reproducibility of stature in pose 1 and in contrast to Jensen and Rudin who successfully reproduced the stature piecemeal in a case study (3). However, this was carried out in 2D so measuring in 3D in the present study might have enhanced the variability.

This can be supported by comparing the inter-observer box-plots for the apex-point in Figs. 4 and 5; it can be seen that it could be better reproduced in the vertical direction alone than in 3D space.

Furthermore, Table 6 shows differences of such magnitude between poses 1 and 2 that none of the body segment lengths could contribute to identification if a given perpetrator was recorded in pose 1 and the suspect in pose 2. The differences observed could partly be caused by the extreme differences in joint position of the hips, shoulders, and elbows between the two poses. This might have influenced the observers' perception of the points. The different joint positions would also explain the tendencies to systematic differences between the two poses. A pose with flexion only present in the sagittal plane—like the one side of the body when walking—might have resulted in body segment lengths in better agreement with pose 1. Nonetheless, precautions should also be taken for differences in posture that will modify the segment length, e.g., a bowed back will affect the measure of the trunk. If only one or few images are available from the crime scene, we therefore suggest recording the suspect in the same pose as the perpetrator to minimize this source of error.

In this study, the mean difference for all subjects generally approached zero in Tables 4 and 5 indicating no systematic differences between the determinations of segment lengths within the same pose. If more images from the crime scene are available, it would be possible to measure several poses and use the mean as proposed by other studies (13,14). In this case, it could be expected that the mean difference of the several determinations of each measure also would approach zero. The use of the mean may probably result in a more accurate determination so all the body segment lengths presented in this study possibly may be used to distinguish between men of the same stature if several images are available. Further research is needed to clarify this.

It has also been suggested to use an approach that locates and calculates the 3D position of points automatically based on a single 2D image (15–18). However, these methods require the use of a biomechanical model combined with a number of control points on the body that have to be placed manually so the problem of locating the body-points accurately remains to be solved.

Measuring stature and segment lengths of the perpetrator from surveillance video has the possibility of becoming a valuable forensic tool because the measures are an integrated part of the offender. At present, the method can be used effectively to exclude a suspect if the anthropometrical measures of the suspect and perpetrator are entirely different from each other. On the other hand, if the perpetrator and suspect do have similar measures, we can only state in court that we cannot exclude the suspect as the perpetrator. However, if both perpetrator and suspect are very short or tall, this can also be a valuable statement. To give a more specific statement of the value of evidence, a database for the population of subjects has to be known (19) such as the reference base used in this study. If the reproducibility of localizing body-points can be enhanced it could be possible to provide the court with a more specific value of the evidence—given that the person in question is known to belong to the same group of people as included in the database.

Conclusions

Photogrammetry should be used with caution in forensic medicine. We found that stature and shoulder height could be reproduced within a few centimeters in ideal situations. However, other body segment lengths may not contribute to identification of subjects with similar stature due to low reproducibility of body-points compared to the expected variability of body segment lengths within subjects of similar stature. To improve reproducibility, images of perpetrator and suspect in same pose and with flexed joints of the extremities should be used if possible. Precautions should be taken against inter-observer variability.

References

1. Knussmann R. Methoden des morphologischen vergleichs in der forensischen anthropologie. In: Knussmann R, editor. Anthropologie—Handbuch der vergleichenden biologie des menschen. Stuttgart & New York: Gustav Fischer Verlag, 1988;368–407.
2. Lynnerup N, Vedel J. Person identification by gait analysis and photogrammetry. J Forensic Sci 2005;50(1):112–8.
3. Jensen SC, Rudin LI. Measure: an interactive tool for accurate forensic photo/videogrammetry. Proceedings of the SPIE—The International Society of Optical Engineering. In: Rudin LI, Bramble SK, editors. Investigative and trial image processing. San Diego, CA: SPIE, 1995;73–83.
4. Daubert v. Merrell Dow Pharmaceuticals, Inc., 509 U.S. 579 (1993).
5. PhotoModeler Pro [computer program], Version 5.0. Vancouver: Eos Systems Inc., 2003.
6. Wirhed R. Anatomi og bevægelseslære i idræt, 2nd ed. Örebro: Harpoon Publications AB, 2002.
7. Netter FH. Atlas of human anatomy. Basle: CIBA-GEIGY Corporation, 1989.
8. Hansen K, Feveile H, Finsen L, Jensen C, Jensen A, Merkel J, et al. Kropsmål for danske arbejdstagere; Antropometriske mål på 467 danske arbejdstagere. Copenhagen: The National Institute of Occupational Health, 1998; Report No.: 48.
9. Gordon CC, Churchill T, Clauser CE, Bradtmiller B, McConville JT, Tebbets I, et al. 1988 Anthropometric survey of U.S. army personnel: summary statistics interim report. Natick, MA: United States Army Natick Research, Development and Engineering Center, 1989 Report No.: NATICK/TR-89/027.
10. Weisberg S. Simple linear regression. Applied linear regression. Hoboken, NJ: Wiley-Interscience, 2005;19–46.
11. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986;1(8476):307–10.
12. Microsoft® Office Excel 2003 [computer program], Version 11.8146.8132 SP2. Redmond, WA: Microsoft Corporation, 2003.
13. Criminisi A, Zisserman A, Van Gool LJ, Bramble SK, Compton D. New approach to obtain height measurements from video. Proceedings of the SPIE—The International Society of Optical Engineering. In: Higgins K, editor. Investigation and forensic science technologies. Boston, MA: SPIE, 1999;227–38.
14. Klasén LM, Fahlander O. Using videogrammetry and 3D image reconstruction to identify crime suspects. Proceedings of the SPIE—The International Society of Optical Engineering. In: Rudin LI, Bramble SK, editors. Investigative image processing. Boston, MA: SPIE, 1997;162–9.
15. Barrón C, Kakadiaris IA. On the improvement of anthropometry and pose estimation from a single uncalibrated image. Mach Vis Appl 2003;14(4):229–36.
16. Mori G, Malik J. Recovering 3D human body configurations using shape contexts. IEEE Trans Pattern Anal Mach Intell 2006;28(7):1052–62.
17. Yang F, Yuan X. Human movement reconstruction from video shot by a single stationary camera. Ann Biomed Eng 2005;33(5):674–84.
18. Ambrosio J, Abrantes J, Lopes G. Spatial reconstruction of human motion by means of a single camera and a biomechanical model. Hum Mov Sci 2001;20(6):829–51.
19. Lucy D. Evidence evaluation. Introduction to statistics for forensic scientists. Chichester, England: John Wiley & Sons Ltd., 2005.

Additional information and reprint requests:
Peter Kastmand Larsen, M.Sc.
Laboratory of Biological Anthropology
The Panum Institute
Blegdamsvej
Copenhagen 3DK-2200
Denmark
E-mail: pklarsen@sund.ku.dk