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TECHNICAL NOTE

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Person Identification by Gait Analysis and Photogrammetry

ABSTRACT: Surveillance images from a bank robbery were analyzed and compared with images of a suspect. Based on general bodily features, gait and anthropometric measurements, we were able to conclude that one of the perpetrators showed strong resemblance to the suspect. Both exhibited a gait characterized by hyperextension of the leg joints, and bodily measurements did not differ by more than 6 mm on average. The latter was quantified by photogrammetry: i.e., measuring by using images of the perpetrator as captured by surveillance cameras. Using the computer software Photomodeler Pro®, synchronous images from different cameras were compared and concurrent body features were identified. The program could then render the perpetrator as a three dimensional, high-precision, scalable and measurable object.

KEYWORDS: forensic science, forensic anthropology, image analysis, surveillance, identification

As part of our investigations of a bank robbery, which had involved murder, we carried out a forensic anthropological assessment of one of the two perpetrators involved. The assessments were based on surveillance videos from the scene, as well as subsequent comparisons with video footage of suspects, and included analyses of bodily proportions, gait and bodily measures by photogrammetry.

Photogrammetry literally means measuring by photography. As such, photogrammetry is a technique as old as photography. Photogrammetry is extensively used in surveying, mapping and architecture, but also more recently in forensic medicine, and may include measurement of unknown values by use of known values within single images (1–3). Another basic application for photogrammetry is measuring objects in a three dimensional space, using photographs of the object taken from different sides and angles. Similar points on the different photographs are identified and a computer program can then calculate the x, y, z-coordinates of the points, thus creating a virtual model of the object. If the camera that took the photographs of the object has been calibrated, a true scale model is made. We used Photomodeler® Pro (4), a software package that allows the above operations. The basis for using photogrammetry in this case was the realization that the perpetrator moved around in the bank and was captured by two cameras simultaneously.

This paper presents the image material at our disposal, the results of our analyses with special emphasis on the use of photogrammetry, and how the results were interpreted and presented in court.

The Case History

On June 21th, 2002, a bank in the town of Aalsgarde, Denmark, was robbed. Two perpetrators, clad in dark clothes and wearing full face motorcycle helmets, ran into the bank and threatened the bank clerks to open the various safe boxes. One of the perpetrators remained standing in the front part of the bank as lookout, while the other bagged the money. Just after entering the bank, a gun was passed from one perpetrator to the other, resulting in the lookout standing with the gun. Meanwhile, outside the bank, a man had noticed that a robbery was under way and decided to interfere and hinder the robbery. The perpetrators had parked a large motorcycle as their getaway vehicle just outside the entrance. Seeing this, the man tried to turn over the motorcycle using his car: he simply backed into the motorcycle. The perpetrator on lookout heard the noise of this attempt, and ran out of the bank, and fired a shot into the car. The bullet passed through the rear window killing the victim instantly. Seconds later the other perpetrator ran out the bank, and they made their getaway on the motorcycle, changing to a car in a nearby forest and then driving away at high speed.

The Case Image Material

We had the following imagery at disposal for our analyses.

Video Imagery from the Bank Surveillance System

The events of the bank robbery were recorded by multiple video cameras in the bank. In all, six cameras were mounted and in operation. Two of the cameras provided very useful images. One camera was placed just inside the porch pointing inwards, thus showing the front part of the bank clearly. This camera, CAM1, was b/w (Fig. 1*a*). The other camera was mounted at the very rear of the bank, pointing outwards, thus also showing the front area of the bank. This camera, CAM6, was a color camera (Fig. 1*b*). CAM1 was set to record four frames per second, while CAM6 was set to a lower rate of two frames per second. The cameras recorded to a digital system, Digi-Eye®, running on a PC-Windows platform. The software is proprietary, but enables export of still images in

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FIG. 1—*Images showing the field of view of CAM1 and CAM6. The two images are almost simultaneous. CAM1 was mounted in such a way that it filmed through a mirror, flipping the recorded images. In the figure, this has been reversed.*

FIG. 2—*Images from police DV cameras showing the two situations where the suspect was filmed walking down a corridor and walking in a courtyard (suspect to the right).*

ordinary bitmap (bmp) format. We were given use of the software enabling us to run the videos on our computers. We received all footage from all cameras from the time of entry of the perpetrators to 2 s after they exited. In all the perpetrators were present in the bank for 3 min. During the robbery, the perpetrator on lookout stood within the field of view of the two cameras (CAM1 and CAM6). Because this person moved around mainly in the front area of the bank, he had been filmed in full for almost 2 min, unlike the other perpetrator who, walking behind desks, etc., was not visible the same way. We produced a multitude of still images of the perpetrators. We did not use edge-sharpening tools, special filtering or the like.

Video Imagery of the Suspect

We obtained two videos of the suspect: one showed the suspect walking along a corridor (total time: 31 s). The video was filmed by a policeman using an ordinary Digital Video (DV) camera. The other video, also filmed with an ordinary DV-camera, was mainly an outdoor shoot, showing the suspect walking around a yard (total time: 1 min and 35 s.) (Fig. 2*a*–*b*).

The Case Analyses

We carried out comparative analyses between the perpetrator and suspect in three stages: 1. an anthroposcopic, morphological assessment of bodily features and general proportions; 2. an anthroposcopic, morphological assessment of the gait, i.e., the body movement; and 3. a photogrammetrical analysis of bodily proportions of the perpetrator and the suspect.

Body Morphology

We compared images of the suspect with the perpetrator in order to note such bodily features and proportions that might indicate concordance as well as incongruity. Obviously, due to the use of helmets (unlike, e.g., a tight fitting stocking or balaclava) and loose fitting clothing, only very general bodily features could be noted. However, several bodily features did seem fairly concordant. We noted a similarity in body proportions, stance and general features of, e.g., the back and shoulders (Fig. 3): both suspect and perpetrator displayed rather rounded shoulders with a wide neck. Likewise, the waist–shoulder proportions were consistent. The curvature of the spine and resultant morphology of the back was also very similar.

FIG. 3—*Comparison of body morphology of perpetrator and suspect.*

FIG. 4—*Comparison of gait between perpetrator and suspect. Arrows point to knee joint hyperextension.*

We realize that such an assessment can only be very approximate due to the clothing, but we viewed this part of the analysis as an introductory exercise. If at this point general body features clearly where incongruous, there would be no use for further analyses.

Gait

The long, uninterrupted video sequences and the rather good frame-rate of CAM1 made it possible for us to analyse and compare the gait. It was early noticed that the perpetrator had a rather wide gait, characterized especially by hyperextension of the knee joints, as well as rather outward pointing feet (Fig. 4). We felt this was indicative of pes equivarus, with a clearly seen convex flexion of the knee joint in the frontal plane. Also, a rather pronounced "swagger" in the gait was observed, with the shoulders describing a pronounced side-to-side movement. We identified similar features in the videos of the suspect (Fig. 4).

Photogrammetry

As noted above, the basis for photogrammetrical analysis is multiple photographs of an object from different angles. In this case, we

FIG. 5—*Screen shot of Photomodeler Pro® interface, showing selection of points. In the image on the left a point ("neck") indicated by the label "525" has been selected. To select the similar point in the image on the right, which is from the other camera, the software shows the epiline (line of sight) as calculated from the first image. The point to be selected now must fall on this line, as well as being anatomically concordant with the first image.*

needed simultaneous photographs, or still images, of the suspect, captured in full stature. In all, CAM1 had 71 s of footage and 278 frames, whereas CAM6 had 79 s of footage, but only 146 frames. The frames from the two cameras were not saved at the same timemarks, but frames were "rotated" to the harddisk between the cameras. The effective timemark difference between frames from CAM1 and CAM6 was 9/100s, implying that the measurement only could be made when the perpetrator was standing still.

The cameras first had to be calibrated in Photomodeler Pro®. The calibration is done by placing several targets (fiduciary points) in the bank and taking photos with a digital camera. These measured points are subsequently imported as control points and a feature in the computer program is then able to calibrate the video cameras and also calculate the exact placement of the cameras. After calibration, we focused on three situations where the perpetrator stood still and we selected the frames from the two cameras showing these situations almost simultaneously (see Fig. 1). These six frames were read into the program, and concurrent points selected.

The selection of concurrent points merits special attention: First specific points, e.g., the knee joint and ankle joint, are selected in a photo from CAM1. This selection is made by judging anatomical landmarks, clothing displacement, comparison with images just before and after the chosen photo, etc. When then focusing on the photo from CAM6, the program indicates the epi-lines (the "line of sight") from the first photo, as well as a line connecting the two joints (Fig. 5). When now selecting the similar points in this photo, it is immediately apparent how good the fit is, and whether the points selected in the first photo are adequate. Thus, the 3-D coordinates are calculated not only by a simple averaging of points chosen from two photos, but reflect a dynamic process where the tightness of the intersections of the epilines is minimized (4).

Based on above points, three line models were produced (Fig. 6). The figure also shows various fiduciary points as well as several control measures. The photogrammetrical analysis yielded a table of body measures for each of the three line models, and an average of the bodily measures could then be calculated (Table 1).

Because the suspect declined to participate in an on-scene recreation of events, or to be measured, the police instead obtained the two video footages of the suspect walking inside the police headquarters and in the police building courtyard. This, however, yielded footage with only one camera. We were able to work around this problem as the police corridor provided us with fiduciary points so that a photogrammetrical analyses could be carried out (Fig. 7). Basically, we could identify a situation where the suspect could be "projected" onto a plane, which then allowed us to obtain the bodily measures (Table 1).

The error within the scene was determined to be less than 1%, based on comparison between physical measurement of some of the fiduciary points (e.g., desk height) in the bank. Obviously, the errors will be greater for "bodily points" such as joints, midlines, etc. due to masking from clothing, etc. While the above described selection procedure will minimize these errors, they cannot be avoided, which is why we carried out the analyses for three situations so as to allow for averaging and comparison. Indeed, the measurements of the perpetrator showed a high degree of correlation between the three sets of measures: overall the average deviation was 2.03 cm, but when focusing on the measures which reflect bodily lengths and breadths, the average was 1.61 cm. This is because the other measures are measures of height and these are relative to the floor, and thus susceptible to even miniscule differences in stance between the three positions. The calculated average of the three sets of measures for the perpetrator was then compared to the measures of the suspect. Overall deviation was 1.01 cm, and 0.60 cm when focusing on breadths and lengths only.

Case Statement and Court Presentation

In our concluding statement to the police, we noted what image material had been at our disposal, and what manner of image enhancing techniques had been used. We then presented the results of the above analyses, each followed by a separate conclusion, and each conclusion always summing up what features were found to indicate concordance between the suspect and the perpetrator,

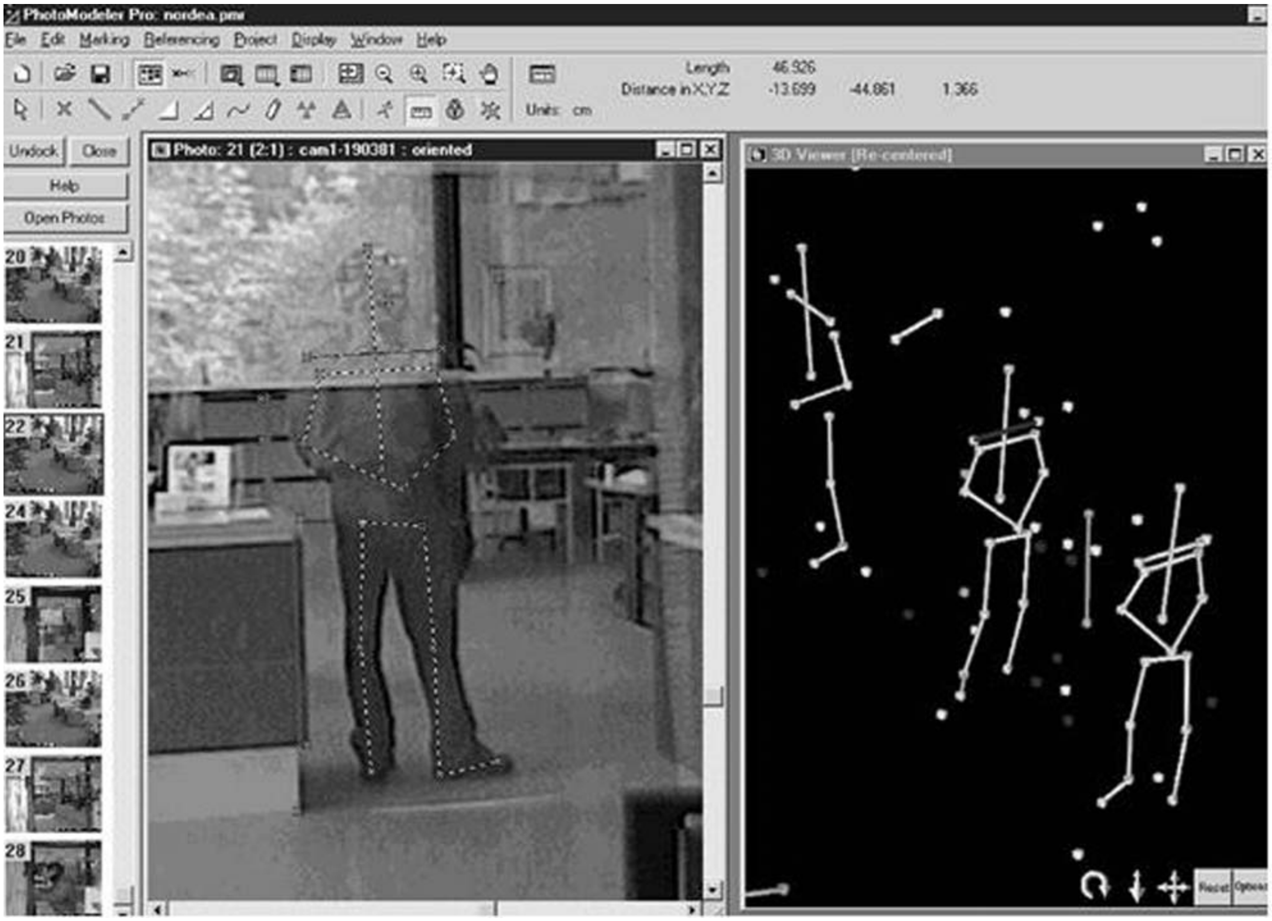

FIG. 6—*Screen shot of Photomodeler Pro® interface, showing placing of reference points of various bodily features in the left panel, and the resultant 3D scale "stickmen" of the perpetrator.*

TABLE 1—*Photogrammetrical measurements. Based on the body feature points two types of measures could be calculated: Heights, i.e. vertical distance from floor to point; and Lengths and Breadths, which are calculated distances between two points. The type of measure is indicated in the table. Three sets of images were used from the surveillance video, resulting in three measurements of the perpetrator (P1–P3) of which an average was then calculated. Measurement of the suspect was done using only one image (see text). Deviation between the measures of the perpetrator and suspect is given in the last column. Average deviation for all measures was 1.0 cm, while it was 0.6 for breadths and lengths. All measures in table in centimetres.*

	Type of Measure	P1	P2	P3	Average (P1–P3)	Suspect	Deviation (Avg. P-Suspect)
Top of helmet	height	185.1	187.0	186.4	186.4		
Top of head	height					182.7	
Upper rim of ears	height					170.7	
Lower rim of helmet visor	height	167.6	168.7	167.6	167.6		
Left shoulder	height	147.8	146.1	148.3	148.3	148.8	0.5
Right shoulder	height	149.2	149.5	149.9	149.9	148.3	1.6
Shoulder breadth	breadth	46.9	48.0	47.1	47.1	46.0	1.1
Left shoulder joint	height	141.9	141.8	142.3	142.3	143.5	1.2
Right shoulder joint	height	143.0	144.3	143.7	143.7	142.0	1.7
Breadth between shoulder joints	breadth	40.2	41.8	41.0	41.0	42.2	1.2
Left elbow joint	height	117.0	116.0	117.4	117.4	118.1	0.7
Right elbow joint	height	118.2	122.0	120.1	120.1	117.6	2.5
Left upper arm	length	25.8	26.1	27.2	27.2	26.9	0.3
Right upper arm	length	25.9	25.1	25.5	25.5	25.7	0.2
Body center	height	107.6	108.8	108.4	108.4	107.5	0.9
Left hip joint	height	88.2	88.1	88.2	88.2	86.7	1.5
Right hip joint	height	87.0	88.5	87.8	87.8	86.5	1.3
Breadth between hip joints	breadth	23.0	23.5	23.3	23.3	23.9	0.6
Left thigh	length	44.5	42.7	43.1	43.1	43.3	0.2
Right thigh	length	43.3	41.9	42.6	42.6		
Left knee	height	43.9	45.5	45.3	45.3	44.3	1.0
Right knee	height	43.7	47.6	45.7	45.7		
Left lower leg	length	43.9	44.1	44.0	44.0	43.4	0.6
Right lower leg	length	44.5	46.5	45.5	45.5		

FIG. 7—*Screen shot of Photomodeler Pro® interface, showing placing of reference points of various bodily features in the left panel, and the "projection" of these features onto a plane perpendicular to the body axis, allowing for measurement. The accompanying policeman was measured as control.*

as well as features that seemed to indicate incongruity. We found no features or measures in any of the three analyses that showed incongruity, rather we only found features which indicated concordance. Emphasis was placed upon our photogrammetrical analyses, as these showed a close concordance in terms of body measures (only a 0.60 cm deviation for seven different length and breadth measures).

We thus concluded that the suspect might very well be identical to the perpetrator, but we stressed that we had no basis for a statistical assessment of the degree of concordance, and that identification by these methods did not constitute identification in terms of, e.g., DNA typing or fingerprinting.

We later had to present our findings in court, where we were allowed to show the video material, as well as the imagery we had used, including a step-by step presentation of the photogrammetrical analysis. While both prosecution and defense challenged us about the degree of error and possible statistical calculations of likelihood, the court admitted our evidence and found it significant.

Discussion

Measurement of stature and bodily proportions has been carried out in numerous investigations where surveillance images of perpetrators could be obtained (5–8). However, the methods employed until now are subject to several errors. Usually, images are produced of measuring devices such as vertical rulers placed at the same location as the perpetrator (9). It is important that these images are produced by the same video cameras as the ones that captured the perpetrator (reverse projection photogrammetry). These images are then overlaid using standard image editing. The major problem is identifying when the measuring device is placed correctly. Ideally, it has to be placed exactly at the same spot where the perpetrator stood in order to result in reliable measurements. This is quite difficult, however, and usually a great many images of the ruler is produced, and only trial and error in terms of overlaying one image after the other enables one to narrow down the most correct superimposition. Likewise, it is very difficult to exactly calculate the error produced if the ruler is not overlaid exactly the spot where the perpetrator stood.

The photogrammetrical method as used in this case, has an advantage in that there is no need to ascertain the position of the perpetrator in relation to a measuring device. After calibration by fiduciary points, the photogrammetrical analysis produces points in a three-dimensional space, and an evaluation of the goodness of fit may be made directly from the tables. Also, controls may be further obtained by measuring specific items like table height, length and breadth of building structures using photogrammetry and comparing this to actual, physical measurements. In the Aalsgaarde case, for instance, we measured the height of a desk (bolted to the floor and not moved between the incident and the analysis) by photogrammetry (result: 89.3 cm) and compared this to an actual physical measurement (result: 90.0 cm). The error was thus 7 mm or less than 1%.

Identification by body morphology (including facial morphology), using both anthroposcopic and anthropometric methods, as well as patterns of body movement, will for the time being not be equal in discriminatory power to other established methods of personal identification, such as DNA-profiling, fingerprinting and dental status (10,11). However, in situations were surveillance imagery is the only record of a perpetrator, these analyses may be useful (12). Use of photogrammetry and analysis of body movement patterns enhance these analyses, and add a better assessment of error. Also, while positive identification will always be problematical, negative identification (i.e., exclusion of several possible suspects) may also be useful for the police (13).

We specifically organize our analyses so that items of bodily morphology that indicate identity between a perpetrator and a suspect are judged alongside items that seem to contradict such identity. Each item may therefore be seen as constituting single pieces of evidence. This renders a statistical approach, for instance the calculation of likelihood ratios for identity, problematical. At present, we do not think it is possible to conclude that there may be a certain degree of probability for identity between a perpetrator and a suspect. This is unlike DNA profiling and fingerprinting, but in these instances the single characters are all well defined and of the same kind respectively, which does allow such calculations (14). For these traits it is also possible to carry out detailed population wide analyses and thus gain statistics on the frequencies of these traits. It is in our opinion much more difficult to ascertain population wide statistics on, say, the frequency of joint hypermobility, as such a trait is of a more qualitative kind. Nonetheless, we do think that showing that the traits of the suspects are fully consistent with those of the perpetrators can be helpful to the trier of fact, as is shown in this case, where the suspects were found guilty of murder, and the court found the evidence significant.

References

1. Thali MJ, Braun M, Wirth J, Vock P, Dirnhofer R. 3D surface and body documentation in forensic medicine: 3D/CAD Photogrammetry merged with 3D radiological scanning. J Forensic Sci 2003 Nov;48(6):1356–65. [PubMed]
2. Thali MJ, Braun M, Brueschweiler W, Dirnhofer R. Morphological imprint: determination of the injury-causing weapon from the wound morphology using forensic 3D/CAD-supported photogrammetry. Forensic Sci Int 2003;132:177–81. [PubMed]
3. Thali MJ, Braun M, Brüschweiler W, Dirnhofer R. Matching tire tracks on the head using forensic photogrammetry. Forensic Sci Int 2003;113: 281–7.
4. Photomodeler Pro® [computer program]. www.photomodeler.com. EOS Systems Inc., 2003.
5. Hoogstrate AJ, Van den Heuvel H, Huyben E. Ear identification based on surveillance camera images. Sci Justice 2001;41:167–72. [PubMed]
6. Thomas CDL. Quantification of facial shape and form. In: Clemet JC, Ranson DL, editors. Craniofacial identification in forensic medicine. London: Arnold,1998;165–76.
7. Iscan MY. Introduction of techniques for photographic comparison: potential and problems. In: Iscan MY, Helmer RP, editors. Forensic analysis of the skull. New York: Wiley-Liss, 1993;57–70.
8. Porter G, Doran G. An anatomical and photographic technique for forensic facial identification. Forensic Sci Int 2000;114:97–105. [PubMed]
9. Knussman R. Methoden des morphologischen Vergleichs in der forensischen Anthropologie. In: Knussman R, editor. Anthropologie. Stuttgart: Gustav Fischer, 1988;386–407.
10. Freckelton I. Identification and the law. In: Clemet JC, Ranson DL, editors. Craniofacial identification in forensic medicine. London: Arnold, 1998;257–66.
11. Yoshino M, Matsuda H, Kubota S, Imaizumi K, Miyasaka S. Computer-assisted facial image identification system using a 3-D physiognomic range finder. Forensic Sci Int; 2000,109:225–37. [PubMed]
12. Geradts Z, Merlijn M, de Groot G, Bijhold J. Use of gait parameters of persons in video surveillance systems. Proceedings of SPIE 2002;4709:16–24.
13. Lynnerup N, Andersen M, Lauritsen HP. Facial image identification using Photomodeler®. Legal Medicine 2003;5:156–60. [PubMed]
14. Aitken CGG. Statistics and the evaluation of evidence for forensic scientists. England: John Wiley & Sons, 1995.

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