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TECHNICAL NOTE

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

Gait Analysis in Forensic Medicine*

ABSTRACT: Recordings from video surveillance systems are used as evidence from crime scenes. It would be useful to perform comparisons between disguised perpetrators and suspects based on their gait. We applied functional anatomical and biomechanical knowledge to analyze the gait of perpetrators, as recorded on surveillance video. Using a structured checklist, which addresses the single body segments during gait, we were able to give a statement concerning the gait patterns. Characteristic parameters were, e.g., varus instability in the knee at heel strike, and larger lateral flexion of the spinal column to one side than the other. Based on these characteristic features, we are able to state with reasonable certainty whether the suspect could be the perpetrator, but it is not possible to identify the perpetrator positively. Nevertheless, we have been involved in several cases where the court has found that this type of gait analysis was a valuable tool.

KEYWORDS: forensic science, gait, recognition, biometry, posture

The ability to recognize other individuals is an essential human characteristic. Identification by gait is a part of this process. Shakespeare made use of this in his play "The Tempest" where Ceres said: "High'st queen of state, Great Juno, comes; I know her by her gait." Psychophysiological studies have proved that the human being can recognize the gender of a walker (1) and friends and colleagues (2,3) with a success rate up to 70–80%. Developments in data technology have made it possible to generate computer models which can identify people's gait with more than 90% success, e.g., (4,5), but these models are still based on a small number of people and require optimal conditions seldom found outside the laboratory (6).

At the Institute of Forensic Medicine in Copenhagen, we are often asked to help the police identify perpetrators based on surveillance recordings of a quality by itself unsuitable for recognition. Instead we combine the basic ability to recognize people with biomechanical knowledge and give statements whether or not a suspect could have been the perpetrator in a given case by comparing the suspect's posture and joint angles during gait with the perpetrator's.

This approach to gait analysis in forensic medicine started with a robbery case in Denmark in 2005 (7) where we found concordances in the gait pattern between suspect and perpetrator, namely, pronounced side-to-side movements of the head and hyperextension in the knee joints.

We have developed a checklist for forensic gait analysis (Table 1). We first describe the general characteristics of the perpetrator's gait and next we analyze each of the joint rotations and segment movements that we have (by trial and error) found relevant for forensic gait analysis. When we have completed this profile of the perpetrator, we compare each item of the list to the recording of the suspect and state whether we find agreement (A), no agreement (N), or comparison not possible (–). An item can be impossible to compare either because the joint rotation/movement cannot be analyzed caused by poor quality of the surveillance recordings, or because the position of the suspect differs too much in some way between the recordings of the crime and the other recording(s), such as differences in shoulder angles between suspect and perpetrator because of elevated shoulders.

Based on this checklist, we give a statement to the police where we point out those features in the gait analysis that we find to be indicative of characteristic concordances between the perpetrator and the suspect. In this paper, we will specifically describe and discuss this approach to gait analysis, combined with photogrammetry and posture analysis, based on a case study.

Case Presentation

In December 2004, a perpetrator robbed a bank in Noerager, Denmark. We were contacted by the police to perform a gait analysis, as they thought the perpetrator had a unique gait. The robbery was recorded by two surveillance cameras. One camera was placed at the entrance, recording the perpetrator in frontal view: walking in, standing and walking in the bank during the robbery, and leaving the bank. The recording frequency was about 5 Hz. The other camera was placed inside the bank recording the cashier's desk from behind and did not record the gait of the perpetrator. However, this camera could be used to measure the perpetrator by photogrammetry and to perform a posture analysis.

Gait Analysis

We instructed the police to establish a covert recording of their suspect from the same angles as the surveillance recordings for comparison.

The gait analysis revealed several characteristic matches between the perpetrator and the suspect. These characteristic features are shown in italic in Table 1, such as outward rotated feet and inverted left ankle during stance (Fig. 1).

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

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TABLE 1—*Checklist for gait analysis. The perpetrator was described and next compared to the recording of the suspect.*

General		
Long/short steps, stiff/relaxed gait with narrow/wide distance between the feet.	*Stiff gait with "heavy" feet*	A
Signs of pathologic gait	None	A
Feet/ankle joint		
Outward rotation	*Marked outward rotation*	A
Inversion/eversion	Neutral at heel strike	A
	Inversion, left ankle in stance phase	A
	Right ankle could not be evaluated—missing recording angle	–
Dorsal/plantar flexion at heel strike	Could not be judged on basis of the existing material	–
Degree of "push-off" at toe-off	Could not be judged on basis of the existing material	–
Knee		
Varus/valgus	Neutral	A
Knee flexion during stance	Could not be judged on basis of the existing material	–
Hip/pelvis		
Pelvis abduction/adduction	Could not be judged on basis of the existing material	–
Pelvis rotation	Very little	A
Pelvis tilt	Neutral/slightly backward	–
Upper body		
Lateral flexion of spinal column	*Asymmetry. Larger flexion to the left side*	A
Forward/backward leaning	Neutral to slight forward leaning	–
Rotation of the upper body during walk	None	A
Shoulders		
Angle in frontal plane	Relatively large angle—shoulders was "hanging"	–
Forward/backward rotation	Neutral/slight forward rotated	A
Neck/head		
Posture in sagittal plane	*Head positioned anteriorly, neck lordosis appeared prominent*	A
Head movements in frontal plane	*Relatively large movements of the head from side to side*	A
Quality of recordings/other precautions	Little material was available to evaluate the perpetrator's gait due to limited walking area in the bank, the perpetrator opening doors, etc. The recording frequency of the robbery was insufficient to evaluate some parameters (especially regarding foot/ankle). The suspect walked with his hands in his coat pockets and thereby lifted the shoulders so the shoulder angle in the frontal plane could not be compared to the shoulder angle of the perpetrator. The suspect was wearing a long coat covering his pelvis so it was not possible to compare pelvis tilt and pelvis abduction/adduction.	

A, agreement; N, no agreement; –, incomparable.

Photogrammetry

It was possible to derive several measures of the perpetrator such as stature, eye height, and shoulder height as shown in the left side of Fig. 2, using photogrammetry in 2D (a measuring frame was placed at the position of the perpetrator and used as drawing plane using the software package PHOTOMODELER® PRO 5 [8]). The suspect (right side of Fig. 2) was recorded from three different cameras simultaneously and a measurable 3D-model was created in PHOTOMODELER® PRO 5. It can be seen that the static measures of the perpetrator and the suspect were in concordance within 3 cm. Furthermore, the differences in the measures can be explained by differences in posture between perpetrator and suspect: the perpetrator stood with the head bowed slightly forward (resulting in decreased stature and eye height), right shoulder elevated (increased right shoulder height), and lowered left shoulder (decreased left shoulder height).

Posture Analysis

The posture of the perpetrator during the robbery was compared to the posture of the suspect based on a covert recording supplied with the images obtained for photogrammetric use. We found concordances between perpetrator and suspect, such as restless stance, anterior positioning of the head showing a neck lordosis, and inversion in the left ankle joint. We also observed some incongruities. The perpetrator had a wider stance, truncus slightly leaned forward, elevated shoulders, and the arms were abducted compared to the suspect. We suspect that these incongruities could be as a result of differences in state of anxiety between the two recording situations. The results were presented to the police using a checklist for posture analysis similar to the list for gait analysis presented here.

In Court

Based on the described analyses, we concluded in our statement to the police that the identity of the perpetrator could coincide with the identity of the suspect but it was stressed that these methods did not constitute identification on the same level of certainty as, say, DNA typing or fingerprinting (7).

Subsequently, we were asked in court to present these features using images and clips from video recordings to illustrate the findings in our statement. The suspect was convicted of robbery and the court found that these analyses were a valuable tool.

Discussion

Geradts et al. (9) studied which gait variables could be used to distinguish between 11 subjects and found very few parameters which could satisfy this criterion. These included the foot angle (degree of outward rotation), the step length, and the mean hip joint angle. We have found several other parameters, which were not included in the study of Geradts et al. (9): inversion/eversion in

FIG. 1—*Both perpetrator (to the left) and suspect showed inverted left ankle (white arrow) during left leg's stance phase and markedly outward rotated feet.*

the ankle during stance, lateral flexion in the dorsal column of the spine, and the knee angle in the frontal plane that would show lateral instability of the knee and signs of a person being bow-legged/knock-kneed. Furthermore, some of the characteristic features we have found were unique, such as limping, which we would not necessarily expect to find present between any two of the 11 randomly selected subjects.

Geradts et al. (9) found that the hip-, knee-, and ankle-joint angle in the sagittal plane were separately unsuitable for identification. Schollhorn et al. (10) concluded that "identification of individuality seems to be impossible with single variables or specific parameters of single variables," so the more characteristics of the perpetrator that can be extracted and combined from the crime scene, the better.

It is our experience that most features can be examined with the camera placed in frontal view. This is in agreement with the work of Jokisch et al. (3) who investigated from which recording angle individuals best could recognize friends and colleagues and found that the frontal angle is superior to half-profile and profile view. Ideally, this camera should be supplemented with a camera in profile view to record the joint and segment angles in the sagittal plane. Geradts et al. (9) suggested a camera placed above the head filming the suspect/perpetrator in transversal view to record the degree of outward rotation of the feet and step length. We find, based on our experience, that a camera placed in this position nearly always prevents the observation of other features than these two, which often can be seen from a camera placed in frontal view. Therefore, we do not recommend this camera position unless it is combined with recordings from other angles.

The recording frequency should ideally be about 15 Hz allowing the examination of dynamic features such as lateral instability in the knee at heel strike. Others have found a similar frequency sufficient for obtaining joint angles (9) and for automatic recognition of gait (5).

Lower recording frequencies may also be sufficient to examine features that are more static as in the case study presented in this paper. In fact, we were prevented from observing only three parameters (dorsal/plantar flexion at heel strike, degree of "push-off" at toe-off, and knee flexion during stance) because of the lowness of the 5 Hz recording frequency. We have had another case that was recorded with about 2 Hz, resulting in a series of still images. However, the perpetrator was recorded in one of the pictures showing a bow-legged left knee. This means that even just one single image of the gait can sometimes be useful, if the gait feature captured can be deemed characteristic.

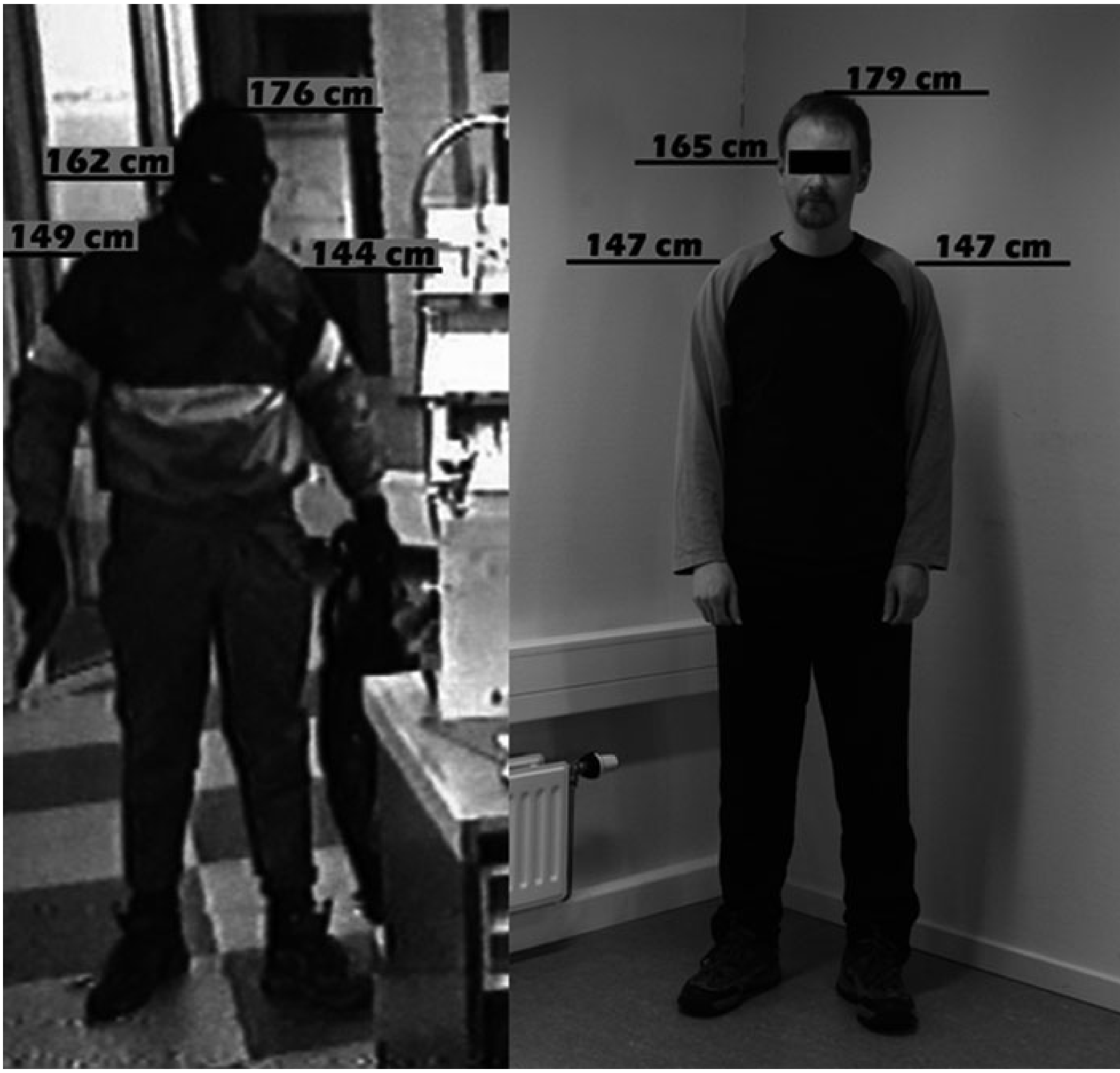

FIG. 2—*Photogrammetric measurement of the perpetrator in the bank (to the left) and the suspect with measures of the stature, the eye height, and left/ right shoulder.*

This type of analysis requires that the police have found a suspect who can be recorded and compared with the perpetrator. We have used both overt and covert recordings of a suspect. There might be a potential problem in using overt recordings such as the suspect consciously tries to modify the gait pattern during recording. We have therefore changed the procedure for recording of a suspect so we always obtain a covert recording and ideally, if the suspect is willing to participate, an overt recording. In an overt recording, we then record the perpetrator from the front, from the back, in profile, and from the same view as the robbery. Furthermore, we instruct the suspect in walking with a speed that matches the velocity of the perpetrator, because the gait speed may influence some of the features. For example, a lateral instability in the knee will be more pronounced at a higher gait speed.

Gait analysis has the potential to produce evidence of value because the gait is an integral part of an individual (11). However, it is at present difficult to improve the analysis with quantifiable measures because the quality of the surveillance material is normally too low to measure, e.g., exact joint angles in frontal or sagittal view. Furthermore, we do not find it possible to identify a perpetrator positively based on analyses of images because we cannot state—to the point of exclusion—in court that no other person could have the same gait pattern based on a given set of characteristics. At present, there is no database to compare such features.

The further development of image analyses for use in forensic medicine depends on better surveillance recordings of potential crime scenes with cameras positioned so they can record the perpetrator: without any obstacles in the way; from frontal, sagittal, and maybe transversal view; and with adequate recording frequency.

We have developed a checklist for gait analysis to help systematize biomechanical gait analysis in forensic cases where the material is of such quality that identification solely based upon viewing the video is precluded.

As such, gait analysis will probably never be evidence as strong as fingerprints or DNA, but may be useful if no conclusive evidence is available (7,12). On the other hand, gait analysis may be used, especially when combined with photogrammetry (13), to exclude one or more suspects.

References

1. Kozlowski LT, Cutting JE. Recognizing the sex of a walker from a dynamic point-light display. Percept Psychophys 1977;21:575–80.
2. Cutting JE, Kozlowski LT. Recognizing friends by their walk: gait perception without familiarity cues. Bull Psychonomic Soc 1977;9:353–6.

3. Jokisch D, Daum I, Troje NF. Self recognition versus recognition of others by biological motion: viewpoint-dependent effects. Perception 2006;35(7):911–20.
4. Cunado D, Nixon MS, Carter JN. Automatic extraction and description of human gait models for recognition purposes. Comput Vis Image Underst 2003;90:1–41.
5. Urtasun R, Fua P. 3D tracking for gait characterization and recognition. Lausanne, Switzerland: Computer Vision Laboratory, Swiss Federal Institute of Technology, 2004. Report No.: IC/2004/04.
6. Nixon MS, Tan TN, Chellappa R. Human identification based on gait. New York: Springer Science+Business Media, Inc., 2006.
7. Lynnerup N, Vedel J. Person identification by gait analysis and photogrammetry. J Forensic Sci 2005;50(1):112–8.
8. PhotoModeler Pro [computer program]. Version 5.0. Vancouver, CA: Eos Systems Inc., 2003.
9. Geradts ZJ, Merlijn M, de GG, Bijhold J. Use of gait parameters of persons in video surveillance systems. In: Geradts ZJ, Rudin LI, editors. Proceedings of the SPIE—The International Society of Optical Engineering. Investigative Image Processing II; 2002 Apr 4; Orlando (FL). Orlando, FL: SPIE, 2002;16–24.
10. Schollhorn WI, Nigg BM, Stefanyshyn DJ, Liu W. Identification of individual walking patterns using time discrete and time continuous data sets. Gait Posture 2002;15(2):180–6.
11. Lucy D. Evidence evaluation. Introduction to statistics for forensic scientists. Chichester: John Wiley & Sons Ltd., 2005;85–103.
12. Klasén LM, Fahlander O. Using videogrammetry and 3D image reconstruction to identify crime suspects. In: Rudin LI, Bramble SK, editors. Proceedings of the SPIE—The International Society of Optical Engineering. Investigative Image Processing; 1996 Nov 19; Boston (MA). Boston, MA: SPIE, 1997;162–9.
13. Larsen PK, Hansen L, Simonsen EB, Lynnerup L. Variability of bodily measures of normally dressed people using PhotoModeler Pro. In: Beraldin J-A, Remondino R, Shortis MR, editors. Proceedings of the SPIE—The International Society of Optical Engineering. Videometrix IX; 2007 Jan 29; San Jose (CA), Vol. 6491. San Jose, CA: SPIE, 2007;64910Z.

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