USE OF PHOTOGRAMMETRY AND BIOMECHANICAL GAIT ANALYSIS TO IDENTIFY INDIVIDUALS

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ABSTRACT

Photogrammetry and recognition of gait patterns are valuable tools to help identify perpetrators based on surveillance recordings.
We have found that stature but only few other measures have a satisfying reproducibility for use in forensics.
Several gait variables with high recognition rates were found. Especially the variables located in the frontal plane are interesting due to large inter-individual differences in time course patterns.
The variables with high recognition rates seem preferable for use in forensic gait analysis and as input variables to waveform analysis techniques such as principal component analysis resulting in marginal scores, which are difficult to interpret individually.
Finally, a new gait model is presented based on functional principal component analysis with potentials for detecting individual gait patterns where time course patterns can be marginally interpreted directly in terms of the input variables.
In this presentation, the above methods will be discussed exemplified with forensic cases.

1. INTRODUCTION

Recognition of gait patterns has been studied intensively during the last decades both with respect to examining differences between groups in biomechanical gait analysis and to identify perpetrators based on surveillance recordings.

At the Unit of Forensic Anthropology, University of Copenhagen, the police provide us with surveillance recordings from crime scenes and of suspects. Based on these recordings we conduct forensic image analyses such as deriving body measures by use of photogrammetry, matching of facial characteristics and biomechanical analyses of gait. The work results in statements to the police which are used as evidence in court.
In a series of studies we have examined photogrammetry and gait analysis in order to develop and validate the use of photogrammetry and gait analysis in forensics.

Figure 1 – Inverted ankle during stance.

2. STUDIES

2.1 Gait analysis in Forensic medicine

In the first study we described how biomechanical gait analysis could be applied to use in forensics [1].
We have combined the basic human ability to recognize other individuals with functional anatomical and biomechanical knowledge, in order to analyze the gait of perpetrators as recorded on surveillance video. The perpetrators are then compared with similar analyses of suspects.
Using a structured checklist, which addresses the single body segments during gait, we give a statement to the police as to whether the perpetrator has a characteristic gait pattern compared to normal gait, and if a suspect has a comparable gait pattern. We have found agreements such as: limping, varus instability in the knee at heel strike, larger lateral flexion of the spinal column to one side than the other, inverted ankle during stance (Figure 1), pronounced sagittal head-movements, and marked head-shoulder posture.
Based on these characteristic features, we state whether suspect and perpetrator could have the same identity but it is not possible to positively identify the perpetrator. Nevertheless, we have been involved in several cases where the court has found that this type of gait analysis, especially combined with photogrammetry, was a valuable tool.
The primary requisites are surveillance cameras recording with sufficient frequency, ideally about 15 Hz, which are positioned in frontal and preferably also in profile view.

 ISSN 2076-1465

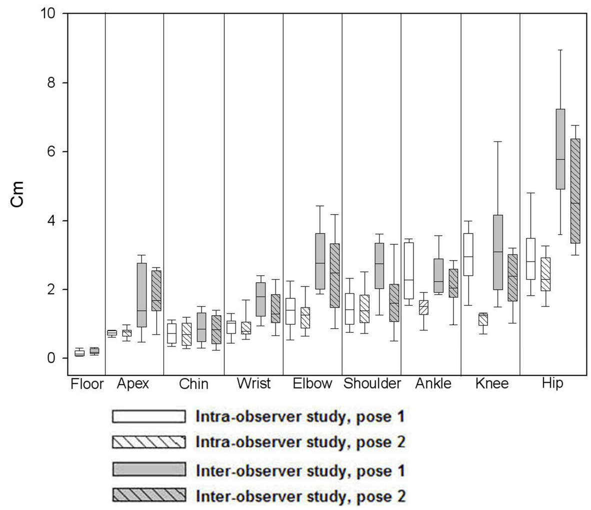

Figure 2 – Box-plots of the differences between two determinations of points. The whiskers show the 10th and 90th percentile. Notice the low reproducibility of all points compared to a well defined point on the floor (except the intra-observer location of the apex).

2.2 Variability of bodily measures using photogrammetry

Photogrammetry is used in forensics 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 remained to be established.
In the second study [2], we therefore quantified the interobserver variability (between two observers) of locating body-points and deriving bodily measures (height to floor and segment lengths) based on these points using 3D photogrammetry (PhotoModeler Pro 5, EOS systems) of fifteen everyday clothed male subjects (mean stature: 181.7 cm, standard deviation: 5.5 cm) Each subject was recorded in two different poses: each subject's normal standing posture (pose 1) and a posture with marked flexion in the joints of the extremities (pose 2). One of the observers repeated the process two months later to establish the intra-observer variability based on eight of the subjects. These eight subjects were selected so the stature of this sub-group and the original group were evenly distributed.

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 and upper prediction limit which represents the largest expected difference (worst-case scenario) between two new determinations on a new subject.

The 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 differences in placement of the points used to determine segment lengths are shown in figure 2. Only the reference-point on the floor has good reproducibility. 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.

The following segment lengths were determined based of the body points: head height, trunk, shoulder width, lower arm, upper arm, lower + upper arm, calf, thigh and calf + thigh. 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 [3]. The standard deviation x 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 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 [4]. The prediction limits for measured differences of the head height were in pose 1 less than half the predicted normal variation and is 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 seems to be markedly better reproduced in pose 2 compared to pose 1. These measures could nearly fulfill the criteria for being a possible contributor to distinguish between men of similar stature.

All segment lengths had lower reproducibility limits in the inter-observer study than in the intra-observer study and no measures could contribute to distinguish between people of similar stature.

Two studies [5,6] 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.

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 [7]. 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 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 the 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 basis of some of 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 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.
It has also been suggested to use an approach which locates and calculates the 3D position of points automatically based on a single 2D image [8-11]. 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.

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 [7,12]. In this case, it could be expected that the mean difference of the several determinations of each measure would also 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.

In model-based approaches in computer vision such as [13] the joint centers are located by use of algorithms and joint angles are estimated. It would be interesting to investigate whether such techniques could be applied to improve the estimation of segment lengths.

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 anthropometric measures of the suspect and perpetrator are entirely different. 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 (Lucy, 2005) 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.

2.3 Gait recognition using biomechanical variables

Recognition of gait patterns has been studied intensively during the last decades. Different gait strategies have been elucidated by applying different waveform analysis techniques to biomechanical gait data and it has been shown that individuals can be identified using joint angles in the sagittal plane. However, little is known about additional variables for gait recognition.

In the 3rd study [14] we therefore examined which biomechanical variables (joint moments, joint angles and segment angles from the lower extremities) obtained in 3D in a clinical gait lab (using the marker setup and 3D inverse dynamics approach according to [15] could be used to distinguish between 21 subjects on two different days.

Six trials were recorded for each subject, normalized to 100% step cycle and averaged for each test day. The time course pattern of each variable for each of the 21 subjects from the first day was used as reference. The matching variables from the second day for each subject were tested against the 21 references in order to identify the same subject on the second day.

Four different statistical measures were used to compare the time course patterns of each variable. The first three were relative reliability measures: 1) The Intra class correlation coefficicient (ICC 2,1) [16], 2) the lower bound of the 95% confidence interval of the ICC and 3) Pearson's correlation analysis**.** The fourth measure was a measure of absolute reliability, the mean square residual from the repeated measures ANOVA [17].

In several cases we found a systematic "DC-offset" between the two days, presumably due to variation of marker placement. This systematic bias resulted in lower recognition rates obtained with the ICC and the lower bound of the ICC, which are affected by such systematic bias, compared to the Pearson's correlation analysis and the mean square residual from the repeated measures ANOVA which are unaffected by systematic bias [18].

This off-set could be removed by taking the 1^{st} derivative to the displacement data. Especially the 1^{st} derivative of the joint angular and segment angles in the sagittal and frontal plane provided high recognition rates and it was possible to recognize all subjects by combining three of these variables. This is in concordance with other studies [19-21] which found that combining more variables leads to better discrimination.

The variables in the sagittal and frontal plane seemed to provide higher recognition rates than the variables in the transverse plane. The relatively high recognition rate for each variable is encouraging for the use of gait analysis in forensic medicine where less optimal setup of surveillance systems often restricts the number of gait variables that can be analyzed [1] and the frontal plane (front-view) is in particular interesting because surveillance systems commonly are designed to record subjects in this plane [22].

Furthermore, the joint- and segment angles in the frontal plane showed high inter-individual variation (Figure 3), which make them interesting for use in waveform analyses such as Fourier transformation or principal component analysis.

2.4 New approach for gait data modelling

The variables with high recognition rates found in the previous study seem preferable for use in forensic gait analysis and as input variables to waveform analysis techniques such as principal component analysis. However, these techniques normally result in marginal scores which are difficult to interpret individually.

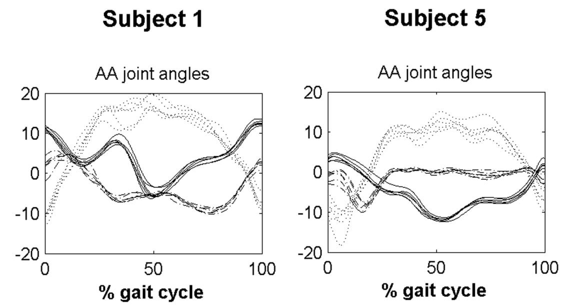

Figure 3 – Joint angles (degrees) for six trials in the frontal plane for two different subjects to illustrate waveform inter-subject variability (hip: solid curve, knee: slash/dotted curve, ankle: dotted curve).

We therefore developed a new gait model [23] based on functional principal component analysis with potentials for detecting individual gait patterns where time course patterns can be marginally interpreted directly in terms of the input variables. The model has potential for recognizing individual gait patterns as shown in Figure 4.

The study is based on the same data as study 3. It can be seen in figure 4 that this model might have a potential for recognition but the day to day variation have a remarkable negative effect illustrated by the subject depicted in blue. It is uncertain whether this between-day variation is caused by variation in the subjects' gait or it can be explained by differences in the experimental setup such as differences in the marker placements as described in study 3. Markerless gait analysis could be applied in an attempt to eliminate this major source of error.

3. CONCLUSION

At present biomechanical gait analysis is a valuable tool in forensic medicine especially when combined with other analyses such as photogrammetry. However, the majority of bodily measures have questionable reproducibility and should be used with caution.

Especially the angular rotation data in the frontal plane have an interesting potential for recognizing individual gait patterns and we have proposed a new gait model, also with potential for recognition purpose, where the outcome can be interpreted in terms of the input variables.

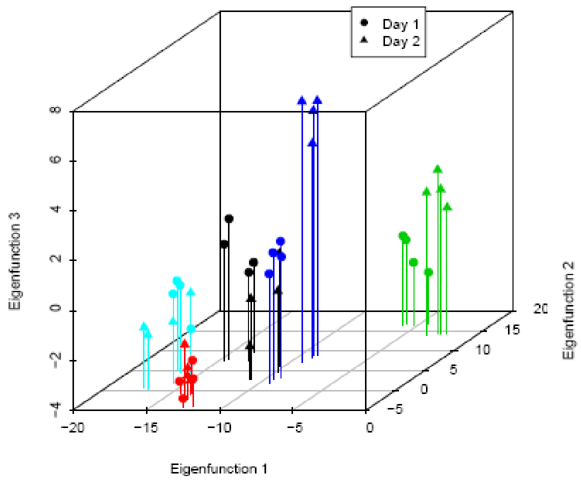

Figure 4 – Projection of gait data (ankle, knee and hip joint angles in the sagittal plane) onto the first three eigenfunctions from five individuals with 8 individual measurements measured on two different days. Points with the same color indicate observations from the same individual.

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