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PAPER

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Comparison of the Performance of Two Methods for Height Estimation

ABSTRACT: In the case study, two methods of performing body height measurements in images are compared based on projective geometry and 3D modeling of the crime scene. Accuracy and stability of height estimations are tested using reconstruction images of test persons of known height. Given unchanged camera settings, predictions of both methods are accurate. However, as the camera had been moved in the case, new vanishing points and camera matches had to be created for the reconstruction images. 3D modeling still yielded accurate and stable estimations. Projective geometry produced incorrect predictions for test persons and unstable intervals for questioned persons. The latter is probably caused by the straight lines in the field of view being hard to discern. With the quality of material presented, which is representative for our case practice, using vanishing points may thus yield unstable results. The results underline the importance of performing validation experiments in casework.

KEYWORDS: forensic science, body height measurement, digital images, video images, CCTV images, photogrammetry, validation, stability

In forensic practice, there is a regular demand for height estimations on perpetrators visible on security camera footage. The results can be used to exclude or gather evidence against suspects and as such are interesting to police, judges, and lawyers.

There are several methods for performing height measurements in images, all based on photogrammetry. Examples of these include:

- *Reverse projection photogrammetry*, cf. (1, 2): here a ruler is projected onto the questioned person to measure his height.
- *Projective geometry*, cf. (3, 4): here vanishing points of parallel lines in the scene are used to obtain height measurements.
- *3D modeling of the perpetrator*, cf. (2): here a 3D model of the questioned person is created out of synchronous images from different cameras.
- *3D modeling of the crime scene*, cf. (5, 6): here a 3D model of the scene is projected onto the image to gain information about heights and distances in the image.

A short description of these methods can be found in (7). In the current study, we confine ourselves to comparing the two techniques that are most commonly used in practice, namely on the basis of projective geometry and on the basis of a 3D model of the crime scene. Our study focuses on measurement uncertainty, a topic not often considered in literature.

In casework, the accuracy of height estimations is validated by performing height measurements on test persons of known height, starting from images taken under similar circumstances (“reconstruction”). Whatever the method used, for each height estimation, there will be a difference between actual and measured height, consisting of a random and a systematic part. Random variation is mainly caused by human interference (operator effects, natural variation). Systematic variation may be introduced by the following factors:

- Depending on the method, either:
  - Construction of vanishing points;
  - Creation of the 3D model and its projection onto the image (camera match);
- Lens distortion at the location of the questioned person;
- Pose of the perpetrator in the questioned image;
- Reconstruction of this pose by test persons;
- Presence and height of head- and footwear;
- Interpretation of head and feet location in the image by operators.

In each examination, the observed systematic bias on test persons is used to adjust the measurement of the perpetrator, and the observed random variation determines a confidence interval for the perpetrator’s height, as described in (8). For validation measurements, we use test persons instead of height charts, because measurements on test persons are informative on the loss in height caused by the pose as well, whereas height charts are not.

In the current case study, questioned images were available of four perpetrators taken by one fixed camera. Height estimations of the perpetrators were requested and treated as separate cases. For each case, reconstruction images were gathered of six test persons. Later on, height measurements were taken by three operators on all images, using both methods, to predict the height of the perpetrators. The procedure was repeated four times.

We are primarily interested in whether resulting confidence intervals for heights of perpetrators are accurate, and secondarily whether they are small. As the actual heights of the perpetrators are unknown, however, we cannot study accuracy directly and will use the measurements on test persons instead.

We will test the accuracy and stability of the measured heights of test persons in two situations. First, we use measurement errors on the *remaining* test persons that result when the *same* camera

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match or vanishing points are used as for a questioned test person. This represents the situation that the orientation of the camera is (almost) the same for both questioned and test persons. There are situations, however, in which the camera has moved in the mean time, and its orientation can only be replicated partially at the time of the reconstruction. This may happen, for example, because the movement of the security camera is restricted, or the camera is difficult to access, e.g., in a cash dispenser. Next to this, it may happen that the captured images deviate from the live view, so that the resulting images have a different alignment even though they seemed aligned during the reconstruction. In these situations, different camera matches and vanishing points have to be used on the questioned and reconstructed images. This is why we study accuracy and stability in the case when camera matches or vanishing points are different.

Materials and Methods

First, we describe the images used in the four cases. Of all four perpetrators, who were well visible on the same security camera, one image each was chosen as the basis of the measuring procedure, as shown in Fig. 1. Lens distortion in the images is negligible. Test persons were positioned in the same stance as the perpetrators. This resulted in $4 \times 7 = 28$ different images, showing either perpetrator or test persons (four cases, six test persons, and one perpetrator per case) on which height measurements were performed.

As stated, the test persons were positioned in the stance of the perpetrator at the crime scene in front of the original camera. As the camera was moved slightly between the crime and the reconstruction, the camera orientation was adjusted using an overlay of a perpetrator image onto the live camera image, in order for the camera perspectives to be as similar as possible. This is illustrated in Fig. 2. Figure 3 shows an example of a questioned image of a perpetrator next to a corresponding test person image. (Notice that Figs. 2 and 3 show that a significant difference between the original image and the reconstructed image remains.)

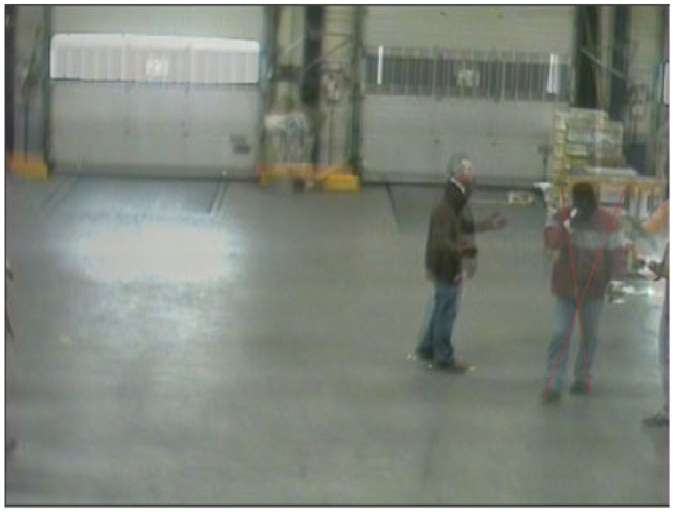

FIG. 2—*Example of an overlay of a perpetrator image and a corresponding reconstruction image.*

The locations of the feet of the perpetrators were marked on the overlay and subsequently on the floor of the crime scene, and the test persons were positioned such that the location and pose were similar to those of the perpetrators. Images of the test persons were captured, and their heights measured in the same way as those of the perpetrators.

Method 1: Projective Geometry (Vanishing Points)

When *a priori* knowledge of the crime scene is available, height measurements can be taken on a single image, without the need of camera calibration, by making use of vanishing points. Essential for a height measurement by *projective geometry* are:

- A reference height of an object in the scene;
- One set of vertical parallel lines (perpendicular to the floor);
- Two sets of horizontal parallel lines in different directions.

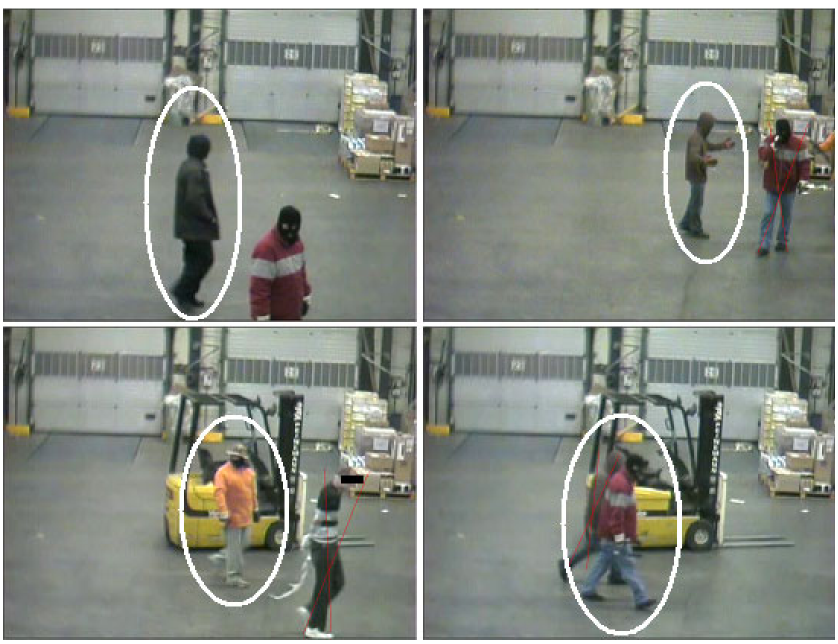

FIG. 1—*Chosen camera images of the four different perpetrators.*

FIG. 3—*Example camera image of a perpetrator (left) and a test person (right).*

Lines that are parallel in 3D will converge at a *vanishing point* when projected on an image. All vanishing points of horizontal lines together form a *vanishing line* (or *horizon*). Construction of the vanishing line of the ground plane and a vertical vanishing point together with a reference height makes it possible to compute a height on the image. The procedure is described in e.g., (3, 4). In Fig. 4, an illustration is given of this method for the performance of body height measurements.

Method 2: 3D Modeling of the Crime Scene

Another method of doing height measurements in images is through the construction of a 3D model of the crime scene by means of photogrammetric software, as described in (6). Photogrammetric software makes use of the fact that 3D coordinates of points can be measured by making photos of the crime scene from different positions. When enough common points are identified on each image, a 3D model of the scene is made.

Next, a human operator links 3D scene points to corresponding points in the questioned image. This makes it possible to determine position, rotation, and focal length of the camera taking the images. The procedure of finding the right camera parameters is referred to as camera matching. Using the camera information, a virtual camera can be placed in the 3D model of the room, looking at the model from the same perspective as the real camera at the real crime scene. On the basis of the 3D model and camera parameters, in software like 3ds Max, it is possible to measure heights and distances on the image. The height of a person is measured by placing a cylinder in the scene (see Fig. 5), from the feet to the top of the head.

Operating Procedure

The operating procedure for the performance of the height measurements was as follows. From each of four cases, seven images were derived as explained earlier: one of the perpetrators and six of the test persons (see Fig. 6).

For each of the 28 images, three different operators performed height measurements on the person in the image, using both methods: projective geometry and 3D modeling of the scene. As the camera parameters on the reconstruction images are not exactly the same as those on the questioned images, measurements on perpetrators and test persons are always on the basis of different vanishing points and camera matches. All measurements were repeated by the operators for *four* times, each time with new camera matches and vanishing points. This is illustrated schematically in Fig. 7.

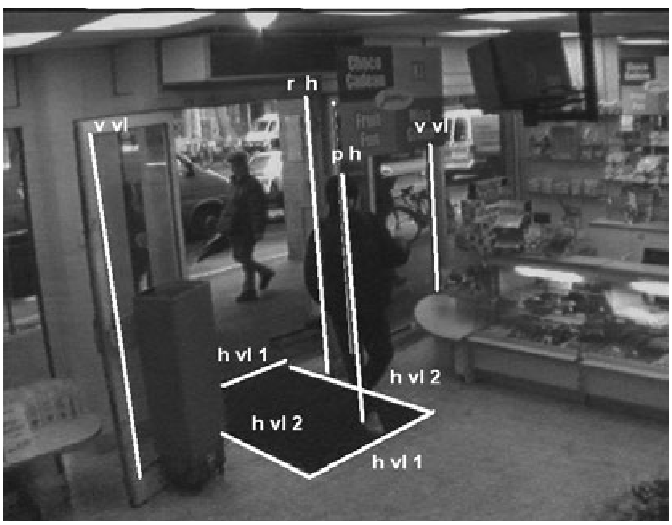

FIG. 4—*Example of a height measurement using projective geometry. Two sets of parallel lines on the ground plane (h vl 1 and 2), a set of vertical lines (v vl), a reference height (r h), and the measured height (p h) are shown.*

FIG. 5—*Example of the 3D model projected onto an image. A cylinder is used to measure the height of the person.*

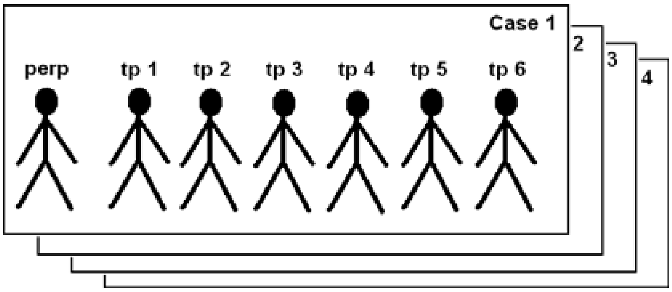

FIG. 6—*Illustration of the images used for height measurements, consisting of four cases, each with one perpetrator and six test persons.*

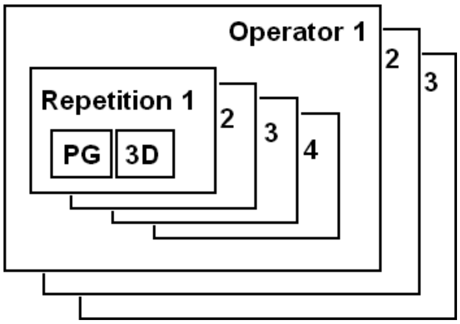

FIG. 7—*Illustration of the measurements performed for every case: three operators, using two methods, repeating their measurements for four times.*

Data Analysis

As a result of the above, the data consist of height measurements $M_{j,k,l,p,q}$, with j denoting the case number, k the method used, l the test person or perpetrator, p the operator, and q the repetition. For each case, method and repetition of the procedure results are averaged over operators.

For all measurements on the *test persons*, the difference with their actual heights is calculated. Systematic and random variations in these differences are then used to predict the height of questioned persons. This is achieved as follows, cf. (8). Suppose a prediction is desired of actual height L of a person on the basis of measured height M and observed differences on test persons $\Delta_1,\ldots, \Delta_n$, with mean $\bar{\Delta}$ and standard deviation S_Δ. Then, under normality assumptions (the Δ_j being independent, normally distributed variables with identical mean and variance), the normalized variable

$$T = \frac{L-(M+\bar{\Delta})}{\sqrt{1+1/n}\, S_\Delta}$$

has the so-called Student's t distribution with $n-1$ degrees of freedom. As a result, given measurement M and observed differences Δ_j, a prediction interval can be determined for an unknown actual height L.

With respect to the accuracy of predictions for test persons on the basis of other test persons, we may now observe whether predicted intervals actually contain the actual height of the test persons. However, for this, we already have to decide on a significance level such as 95%, which is arbitrary. Hence, it is better to study the normalized variable T directly. If the model applies, T has a fixed Student's t distribution, and using the Kolmogorov–Smirnov test statistic, cf. (9), it is possible to test whether outcomes for T differ significantly from the model. All in all, for any combination of method, case, and repetition of the procedure, this leads to p-values describing the quality of fit for the model.

Our analysis is as follows: first, we look whether reported intervals on the individual test persons are correct if determined on the basis of the measurement results for the other five test persons during the same repetition of the measurement procedure. This represents the situation in which the camera orientation is reconstructed properly. Second, we study the prediction of heights of test persons on the basis of results of the other (five) test persons from *another* repetition of the procedure. For the first method, this means that different vanishing points are used for the remaining test persons than for the "query" test persons, for the second method, it means that different camera matches were used. This is relevant when the original camera orientation has changed between incident and reconstruction and cannot be reconstructed properly. Predictions are then based on results given fixed vanishing points or camera matches for the test persons, whereas for the perpetrator, different parameters are used. This step in the analysis tries to imitate this situation.

In the third and final step, predictions of perpetrator heights are studied based on validation measurements on the test persons, measured using a different camera orientation. Here, we look at whether different repetitions of the procedure lead to similar confidence intervals if the original camera orientation cannot be reconstructed properly.

Graphical illustration of our data takes place using *box plots*. In these, the following conventions are followed: boxes denote the interquartile range, whereas the middle line denotes the median of the data. Whiskers show the distance from the end of the box to the largest and smallest observed values <1.5 box lengths from either end of the box. Outliers are depicted by the plus (+) symbol.

Results

For any fixed case, method, and repetition of the procedure, we may predict the difference between actual and measured height of any query test person on the basis of the observed differences from the remaining test persons. As the actual heights of the query test persons are known, for any such combination and query person, we can calculate the normalized variable T described in the section Data Analysis. The variable T is based on the actual height L, measured height M of the questioned person, and observed differences for remaining test persons $\Delta_1,\ldots, \Delta_5$, gathered from the same repetition of the measurement procedure. The variable T describes the measure, in which predicted height "fits" to the actual height of the person.

For each combination of case, method, and repetition, the procedure leads to six normalized outcomes T. Figure 8 shows box plots of the normalized variable T for all six test persons, for all combinations of cases, methods, and repetitions separately.

Assuming accuracy of the prediction model, outcomes for T should be approximately zero, with a standard deviation of circa 1.3 (corresponding to the Student's t distribution with 5 degrees of freedom). By performing a Kolmogorov–Smirnov test, p-values are calculated, describing the quality of fit of the model per combination of method, case, and repetition. We find that at a confidence level of 5%, for both projective geometry and 3D modeling, all of the sets of six outcomes for T are accepted under the model (all p-values are above 0.05), thus predicted heights seem to be reliable.

Different Camera Orientation

To study the effect of a different camera orientation, we repeat the experiment but now use the measurements of remaining test

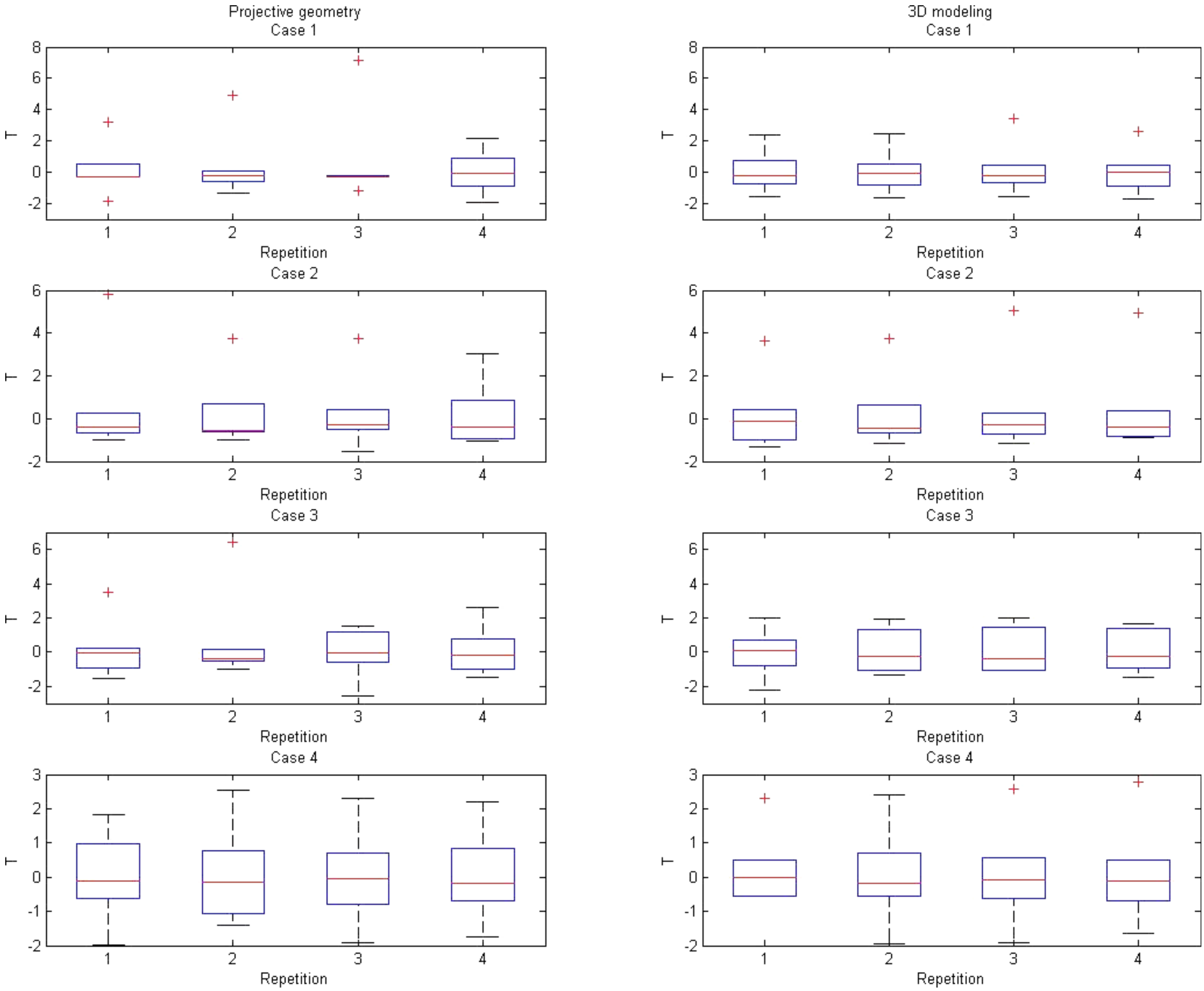

FIG. 8—*Box plots of the normalized variable* T *of all six test persons, using measurements of the remaining test persons within the same repetition of the measurement procedure, for all combinations of methods, cases, and repetitions separately.*

persons from a *different repetition* of the measurement procedure. The relevance of this is that in casework, validation readings may be obtained using different camera settings, which may have an influence on the procedure of predicting heights on questioned persons.

An example is shown in Fig. 9, in which heights for query test persons of repetition 1, 2, 3, and 4 of the procedure are predicted on the basis of validation results for the remaining test persons of repetitions 2, 3, 4, and 1, respectively. (Other combinations show similar results.)

Again, outcomes for T should be near zero with a standard deviation of approximately 1.3, assuming accuracy of the prediction model. In Table 1, p-values are given resulting from use of the two methods, for all cases and repetitions of the procedure. For projective geometry, only two values are higher than 0.05, which means that 14 of 16 sets of six outcomes for T are rejected under the model at a confidence level of 5%. For 3D modeling, only one p-value of 16 is significant (smaller than 0.05). At a 5% confidence level, which implies that 1 in every 20 significant p-values will be random, this is well possible.

We see that under these circumstances, the method based on 3D modeling is much more reliable than the method based on projective geometry.

Stability of Body Height Predictions for the Perpetrators When a Different Camera Orientation Is Used for Test Persons

Finally, we take a look at stability of body height predictions for the four perpetrators, based on validation measurements on the test persons, which were measured using a different camera orientation. In Fig. 10, box plots illustrate the predicted heights for the four perpetrators of the different cases, given fixed case number, method, and repetition of the measurement procedure. Using the projective geometry-based method, we see that results of the first and second repetitions are comparable, the third interval being much higher and the fourth much lower. The latter two do not even overlap. Notice that the results for fixed repetitions of the measurement process are correlated over each of the four cases, because the same vanishing points and camera matches were used. Starting from 3D modeling, results from all different repetitions

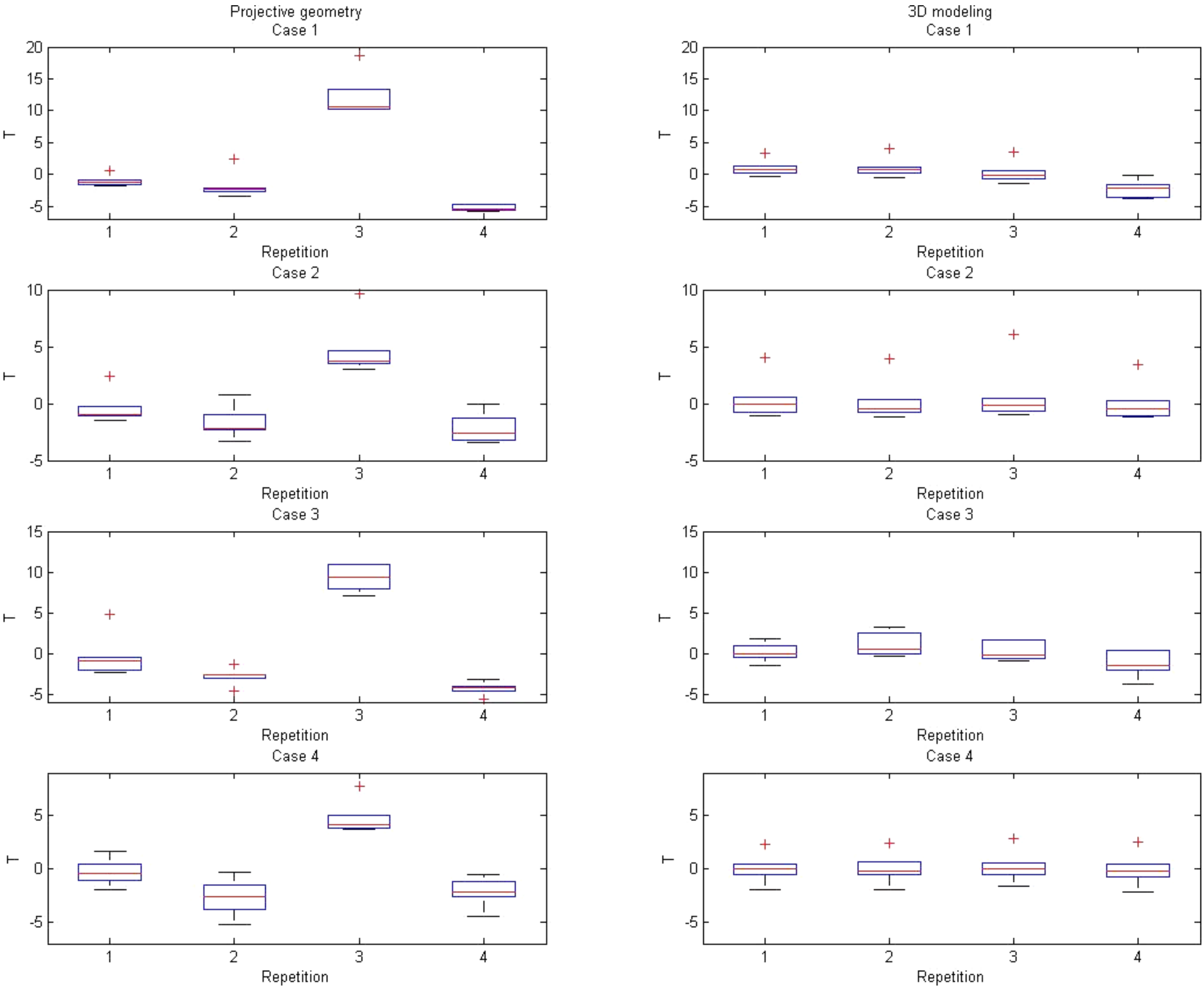

FIG. 9—*Box plots of the normalized variable* T *of all six test persons, using measurements of remaining test persons within a different repetition of the measurement procedure, for all combinations of methods, cases, and repetitions separately.*

yield comparable results, for all four cases, the box plots overlapping.

The above indicates that if the original camera orientation is not reconstructed properly, predicted heights on the basis of projective geometry are less stable under repetition of the procedure than those predicted from 3D modeling.

TABLE 1—*p-Values for the Kolmogorov–Smirnov goodness of fit test statistic, given different methods, cases, and repetitions. Scores are based on validation measurements on test persons from a different repetition of the measurement procedure.*

	Projective Geometry				3D Modeling			
KS	Rep 1	Rep 2	Rep 3	Rep 4	Rep 1	Rep 2	Rep 3	Rep 4
Case 1	0.02	0.00	0.00	0.00	0.23	0.29	0.95	0.00
Case 2	0.15	0.01	0.00	0.00	0.98	0.46	0.94	0.58
Case 3	0.05	0.00	0.00	0.00	1.00	0.22	0.84	0.06
Case 4	0.72	0.00	0.00	0.00	0.99	0.98	0.99	0.91

Conclusion and Discussion

In the case study, two methods for performing body height measurements on persons in digital images were compared in a three stage process. The methods are based on projective geometry and 3D modeling of the crime scene, respectively. First, heights of test persons were predicted based on measurements while using the same vanishing points or camera matches. Here, both methods led to correct predictions.

When the field of view for the questioned image is different from that of the reconstruction images, new vanishing points or camera matches will be used for measurements. The influence of this on performance of the methods was studied by testing the accuracy of height predictions on test persons, based on measurements of the remaining test persons from another repetition of the procedure. Here, predicted heights by the projective geometry method are significantly inaccurate under the statistical model. Height predictions on the basis of the 3D modeling method are accurate.

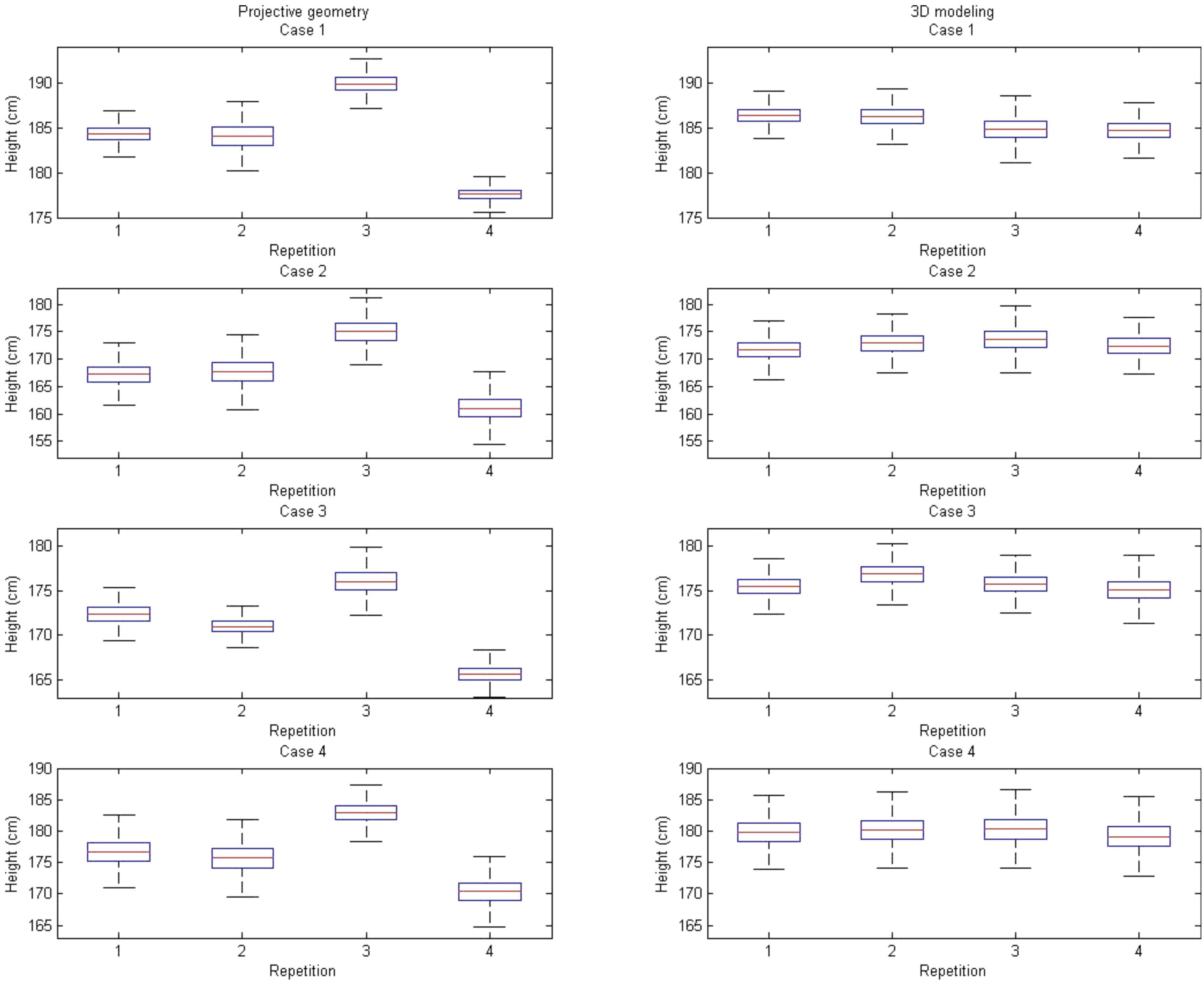

FIG. 10—*Box plots illustrating predicted heights of the four perpetrators for the different cases, based on the four repetitions of the measurement procedure, using either the projective geometry method or the 3D model-based method.*

Third, prediction intervals for perpetrator heights were calculated for each of four repetitions of the measurement procedure, in a situation with differing camera orientations for test persons and perpetrator. Here, the ground truth is unknown, so it is not possible to investigate accuracy of the results. The projective geometry method leads to prediction intervals that are unstable though, sometimes not even overlapping. Intervals predicted via 3D modeling are stable.

It is not the intention of the authors to suggest that performing height measurements using vanishing points is an unreliable procedure. Indeed, this is a well-founded method of performing photogrammetry in images. This is confirmed by the results of the first stage of the procedure, which shows that both methods lead to correct predictions when operators use the same vanishing points or camera matches for all images. However, given the case material at hand, the method based on projective geometry yields inaccurate and unstable results, both:

- When predicting test persons' heights based on the remaining test persons, using new vanishing points and
- When predicting perpetrators' heights based on the test persons, using new vanishing points.

It can be seen in Fig. 2 that questioned and reconstruction images have a considerably different field of view/camera orientation, which may be thought as having a negative influence on the creation of vanishing points. Given the first of the two conclusions though, the problem lies in the interpretation of straight lines in the image, *not* in the changed field of view (in this part of the analysis, the field of view in the images was identical, but new parallel lines were drawn). In the predictions on the perpetrators, both the choosing of parallel lines and the changed field of view may have caused inaccuracy and lack of stability. These results suggest that one should not use the projective geometry method in cases where the alignment of the camera is bad, and lines are not clearly visible.

Moreover, the conclusions are based on images from one particular camera, which might be considered atypical in height estimation procedures and unfair for the study of performance of vanishing points. In our case practice, however, the quality of the material from the case at hand is quite common, even better than usual. Lens distortion and shifted camera orientations are very regularly occurring phenomena, in which case, the experiment described previously is quite relevant.

In general, results of this study underline the importance of performing validation experiments in casework. Measurements on perpetrators should be supported by measurements on test persons, taken under similar circumstances. In particular, when performing height measurements on the basis of vanishing points/projective geometry, in case of lens distortion or parallel lines that are hard to determine, it is important to repeat the measurement process to study the stability of outcomes.

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