Forensic Science International 197 (2010) 48–53

Contents lists available at ScienceDirect

Forensic Science International

journal homepage: www.elsevier.com/locate/forsciint

A hierarchical model for body height estimation in images

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ARTICLE INFO

Article history:
Received 13 July 2009
Accepted 9 December 2009
Available online 18 January 2010

Keywords:
Bayesian inference
Body height estimation
Confidence intervals
Credible intervals

ABSTRACT

In forensic practice, validation experiments performed on known items or persons are used to make predictions on unknown ones. An example of this is body height estimation in digital images. Using a hierarchical statistical model in this case is quite natural as it allows outcomes of the experiment to depend on random effects for test persons and on fixed effects for operators performing the measurements. In the paper, a hierarchical model is described and implemented in WinBUGS to obtain Bayesian credible intervals for perpetrator heights in a case study involving four perpetrators. Comparing the estimated credible intervals of the Bayesian inference to frequentist confidence intervals proposed in the literature, the results that emerge are quite similar, Bayesian intervals being slightly wider. The hierarchical model takes into account the variation within the individual measurements which is ignored by models using observed means over operators. The approach described is applicable for situations in which on the basis of (repeated) measurements on known objects, a prediction is required on a questioned object under the same circumstances. Another example of this is estimating the speed of a vehicle on video footage on the basis of a validation experiment.

1. Introduction

In forensic practice, there is a regular demand for height estimations on perpetrators visible on security camera footage. Height estimates 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. Two important examples include a method based on *projective geometry*, cf. [1,2], using so-called vanishing points of parallel lines in the scene in order to obtain height measurements, and a method based on *3D modeling of the crime scene*, cf. [3,4]. In the latter approach, a 3D model of the scene is projected onto the image to gain information about heights and distances in the image. A general description of methods used for height estimation can be found in [5]. From here on, the paper concentrates on height measurements performed using a 3D model of the crime scene.

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*). The measurements are repeated by several (usually 3 or 4) operators. In [3,4], a statistical model is developed to interpret the data obtained. For each height estimation the difference between actual and measured height is evaluated, consisting of a random and a systematic part. Random variation is supposed to be caused by human interference (operator effects, natural variation). Systematic variation may be introduced by factors such as creation of the 3D model, 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, or interpretation of head and feet location in the image by operators. In each examination, the observed systematic bias on test persons, averaged over the operators, is used to adjust the measurement of the perpetrator, and the observed random variation determines a confidence interval for the perpetrator's height.

Besides the fact that differences are averaged over operators instead of using the raw data, the model described is basically frequentist in nature. This brings up the question how a Bayesian approach to the data analysis will turn out with respect to the resulting point estimates and confidence (in a Bayesian context: credible) intervals.

A casework example involving digital images of four perpetrators in front of the same camera is given in [6]. Here a comparison is made between the methods based on projective geometry and 3D modeling of the scene. It turns out that the first is unstable under repetition of the measurements by the operators,

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0379-0738/$ – see front matter © 2009 Elsevier Ireland Ltd. All rights reserved.
doi:10.1016/j.forsciint.2009.12.020

Fig. 1. Images used in the four cases. Images produced by the same security camera.

whereas the second is stable. In the current case study, the same case material was used, and height estimations of the perpetrators are treated as separate cases. The goal is to:

1. Implement a model for Bayesian inference, using the open source software WinBUGS [7], in order to obtain credible intervals for perpetrator heights.
2. Compare the resulting intervals to the ones obtained using the frequentist approach in [3,4].
3. Quantify evidential value of eventual similarity of estimated perpetrator height and height of a suspect.

In the paper we will confine ourselves to the first two points, which are basically about measurement uncertainty. We attend to the third, which is on strength of evidence of resemblance, quantified by likelihood ratios, in a separate paper. The main problem of the current paper will be in the selection of the right statistical model for the hierarchical set-up.

Section 2 describes how the images were obtained and the data set-up. In Section 3, methods for data analysis are discussed and Section 4 presents the results. The paper concludes with a discussion.

2. Data

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, see Fig. 1. Test persons were positioned in the same stance as the perpetrators in front of the original camera. 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. Measurements are in meters.

Images of the test persons were captured and their heights measured in the same way as those of the perpetrators. Three different operators performed height measurements on the person in the image. All measurements were then repeated by the operators for *four* times, each time with new camera matches. This is illustrated schematically in Fig. 2.

As a result of the above, for each case the data consists of height measurements m_{ijk}, where i denotes the test person or perpetrator, j the operator and k the repetition. Moreover, for all test persons, their actual heights were determined as the average of three measurements under a stadiometer, without foot- or head-wear.

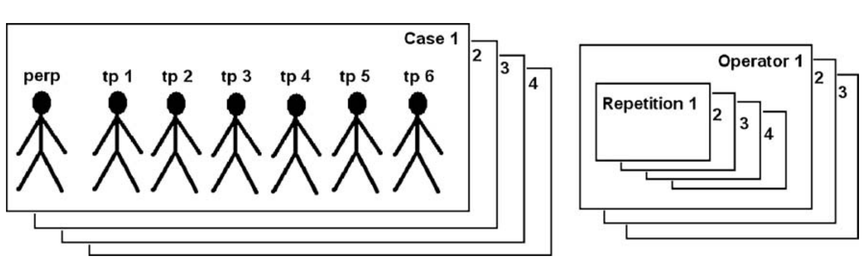

Fig. 2. Design for the repeated measurements. Four cases, one perpetrator and six test persons, three operators, and 4 repetitions.