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Establishing state of motion through two-dimensional foot and shoe print analysis: A pilot study

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ABSTRACT

According to the College of Podiatry, footprints rank among the most frequent forms of evidence found at crime scenes, and the recent ascension of forensic podiatry reflects the importance of footwear and barefoot traces in contemporary forensic practice. In this context, this pilot study focused on whether it is possible to distinguish between walking and running states using parameters derived from two-dimensional foot or shoe prints. Eleven subjects moved along four tracks (barefoot walking; barefoot running; footwear walking; footwear running) while having their bare feet or footwear stained with artificial blood and their footstep patterns recorded. Contact stains and associated bloodstain patterns were collected, and body movements were recorded through three-dimensional motion capture. Barefoot walking prints were found to be larger than barefoot static prints (1.789 ± 0.481 cm; $p < 0.001$) and barefoot running prints (0.635 ± 0.405 cm; $p = 0.006$). No correlation was observed for footwear prints. Running trials were more associated with the presence of both passive and cast off stains than walking trials, and the quantity of additional associated stains surrounding individual foot and shoe prints was also higher in running states. Furthermore, a previously proposed equation predicted speed with a high degree of accuracy (within 6%) and may be used for clinical assessment of walking speed. Contact stains, associated bloodstain patterns and stride length measurements may serve to ascertain state of motion in real crime scene scenarios, and future studies may be capable of designing statistical frameworks which could be used in courts of law.

1. Introduction

As footprints rank among the most frequent forms of evidence [1] found at crime scenes, this pilot study addresses the feasibility of establishing the state of motion of an individual through the analysis of two-dimensional foot and shoe prints. It is proposed that foot impressions are able to provide investigators with a vast array of useful information about the individual who generated them, ranging from likely foot pathologies to constituents of the biological profile [2–7]. There is, however, a scarcity of established methods for deriving kinematic data from foot impressions. In this pilot study, the association between two-dimensional foot and shoe prints and state of motion is addressed and explored.

Some authors have aimed to evaluate kinetic and kinematic parameters through three-dimensional footprints and foot pressure analysis [8–10]. However, there is a lack of studies aiming to associate kinematic data (speed and stride length) with two-dimensional foot and shoe prints. Considering this scenario, there are authors who have illustrated how forensic science can derive useful techniques from palaeontology by characterising a relationship between speed and stride length [11,12]. The use of the equations proposed by these authors in forensic and clinical contexts constitutes a potential research topic, and the repeatability and accuracy of their findings are assessed in this present study.

Bloodstain pattern analysis also comprises an experimental topic of this pilot study, hence possible correlations between stain patterns and state of motion are addressed. Even though fluid mechanics literature does not usually include blood dynamics [13], multidisciplinary teams have recurrently improved the understanding and practice of bloodstain pattern analysis. The findings of this present pilot study may support future research in constructing statistical frameworks for the case assessment and interpretation model.

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This pilot study explores the possibility of determining the state of motion of a person based on parameters derived from two-dimensional foot and shoe prints, especially in forensic contexts. Three experimental topics are covered: two-dimensional foot and shoe prints; bloodstain pattern analysis; and stride length. Future research may indicate the relevance of the reported results for forensic and clinical practice.

2. Materials and methods

This study was approved by the University of Dundee Research Ethics Committee – reference UREC 15178.

2.1. Subjects

Eleven consenting subjects (six males and five females) volunteered to participate in the study. The experiments were performed in the gait analysis laboratory at the Institute of Motion Analysis and Research, in the TORT Centre, Ninewells Hospital and Medical School, Dundee, United Kingdom. Table 1 summarises the assembled subject data.

Exclusion criteria were:

1. Age less than 18 years.
2. Previously diagnosed pathological gait condition.
3. Any abnormal foot pathologies.

2.2. Materials

The Bigfoot Inkless Shoeprint Kit was used to sample foot and shoe prints prior to experiments, with paper size 190 mm × 406.4 mm.

Volunteer subjects were given a standard type of footwear: black Bailey Unisex Canvas Lace Up Padded Plimsolls. Available sizes ranged from 4 to 11 (UK units). Subjects wore this footwear model to complete the two footwear tracks; footwear walking and footwear running.

Each subject moved along four different tracks: barefoot walking; barefoot running; footwear walking; and footwear running. These tracks were composed of thick paper and were completely flat. Each track measured approximately 2.50 m in length. Before entering the actual tracks, subjects moved along an initial distance of 1.12 m for walking tracks and 2.24 m for running tracks.

The substance chosen to serve as artificial blood was the bloodymarvellous™ Dark/Venous Antibacterial Medical Training Blood. It possesses a reportedly similar consistency to real blood; the measured density of the substance was 1.136 kg/m^3.

To record average speed and stride length, the Vicon MX13 high-speed motion capture system was used (200 Hz). This system incorporates eight high resolution cameras of 1.3 megapixels and four high resolution cameras of 4 megapixels mounted above head height. The system was calibrated prior to each individual trial.

2.3. Experimental design

Age (in completed years), height (m), body mass (kg) and compatible footwear size (UK) were all recorded for each subject.

Measurements associated with the three-dimensional motion capture system were also performed for each subject. These measurements were: lower limb height, ankle width, knee width, shoulder-elbow distance, shoulder offset distance, elbow width, and wrist width (all in mm), collected using the Vicon Plug-in Gait measurement protocol [14]. After measurements were recorded, sample static foot and shoe prints were obtained through the Bigfoot Inkless Shoeprint Kit. The volunteer stood upright weight bearing with one foot on the Bigfoot Inkless Shoeprint Kit.

At the beginning of each track, subjects had their bare feet or footwear stained with artificial blood. To accomplish this, subjects were asked to dip their feet in to a tray containing the simulated blood and a paint roller was used to distribute the blood more evenly over the feet or footwear surfaces. This process was repeated for each individual track. Feet and footwear were re-inked prior to commencing each trial. Subjects completed each track at their preferred speed and starting foot.

Fig. 1 illustrates an aerial view of the experiments. In such a setup, two-dimensional foot and shoe prints were obtained in the form of contact stains; artificial blood transferred to paper from stained footwear or barefoot. Paper tracks were stored until the blood was dry, and then a single print of either side from each track was chosen according to quality criteria. Chosen foot or shoe prints were scanned (lossless.jpg format, 600 × 600 dpi) and then physically and digitally stored to avoid contamination of the original data.

The criteria for selecting foot or shoe prints for bloodstain pattern analysis were:

1. Lack of post-experimental contamination and/or damage, such as direct contact contamination, tears and modification of blood patterns due to external factors;
2. Absence of signs of slippage and/or abnormal stride as evident by a blurry or misshapen image;
3. Not the first or last print on track;
4. Absence of any sign of ghosting.

For instances in which more than one print in a given track met all criteria, one of the prints was chosen randomly by the researcher.

Additional impressions were also extracted from some tracks to allow the comparison of footprints generated from the same foot, since bilateral asymmetry was assumed to be significant. Stride length and speed values were recorded through the calibrated three-dimensional motion capture system (Vicon MX13). Stride length was measured between consecutive foot strikes of the same foot.

2.4. Data analysis

Microsoft Excel 2016 was used for digital data analysis. The IBM SPSS Statistics software was used for paired sample *t*-test. The

Table 1
Subject data. Different parameters are shown for the assembled population, which comprised 11 volunteers.

Descriptors	Age (years)	Body mass (kg)	Height (cm)	Lower limb height (cm)	Footwear size (UK units)
Mean	22.45	69.22	172.82	90.87	7.18
Standard Deviation	1.63	14.89	8.98	4.27	1.94
Maximum	25	104.4	195	101.4	11
Minimum	20	52.2	160	84.74	5
Range	5	52.2	35	16.66	6