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Review article

# Forensic footwear examination: A systematic review of the existing literature

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ABSTRACT

Systematic reviews have been shown to be useful tools mainly in terms of identifying research areas, but the approach is less common in forensic science. Systematic reviews in forensic science have generally focused on topics closely linked to medicine or to the general practice of forensic science, such as cognitive bias or misleading evidence. The value of a systematic review is dependent on its transparency and reproducibility and, it is therefore of benefit to follow established guidelines, such as those published by the Cochrane Collaboration and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). This paper applies these guidelines to conduct an effective systematic review of the types of research that have addressed forensic footwear examination. Using this approach, it was found that overall, there is a significant body of research that has been undertaken addressing forensic footwear examination, with 427 papers in the scope of the systematic review. The results showed that the largest proportion of papers published reported the use of an algorithm to produce an automated system to code footwear marks (25.1 %). However, only a small number of papers (1.2 %) related to the actual coding process with limited research into the use of footwear intelligence (2.1 %) and linking of scenes (0.7 %) which would follow on from pattern coding. Papers relating to the recovery and enhancement of footwear marks most frequently reported in the areas of casting (7.3 %), photography (6.3 %), chemical enhancement of marks in blood (5.9 %) and other chemical enhancement (5.6 %). A relatively small proportion of papers identified considered interpretation (15.5 %) and the characteristics of a footwear mark (12.2 %), with the former predominantly focused on general interpretation (5.9 %) and the latter on damage or randomly acquired features (6.1 %). Overall, the review suggested that more research is needed to address the use of footwear intelligence; to understand the properties of footwear prints used to compare and evaluate footwear marks; and to develop a robust, transparent and consistent method to interpret and express the significance of a footwear comparison. The latter would facilitate the clear and unambiguous communication of findings to the Criminal Justice System as a whole, including the expression of the uncertainty of the evidence.

## 1. Introduction

Forensic footwear examination is widely used in the investigation of crime [1]. Although recovery and enhancement techniques for footwear marks and the method for comparing a footwear mark with a shoe or print are broadly standard internationally [1–5], there are currently a number of different models for the evaluation and reporting of findings in the UK and also world-wide [2,6–9].

National and international reports on Forensic Science have highlighted research priorities since 2009 [10–12]. These reports all acknowledge the need for the collection, collation and interrogation of data to support evidence and demonstrate the validity and transparency of evidential opinions. The reports also recognise that more needs to be done to develop a method by which the significance of evidential

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findings and interpretation can be communicated effectively to the courts. This is particularly relevant for footwear evidence following a Court of Appeal ruling [13] where the way in which the forensic footwear evidence was interpreted and presented was criticised by the Court. There are locally held databases in police forces and forensic service providers in the UK, as well as the National Footwear Database, which hold some data to support the statistical evaluation of the evidential significance of footwear evidence. However, footwear evaluation is not fully based on empirical data with the results varying depending on the reference material used to produce the data.

The absence of an effective evaluative interpretation model for forensic science is a risk to the effective communication of the outcomes and the understanding of the significance of marks and traces within the Criminal Justice System [8,10–12].

In the United Kingdom, forensic results are often categorised as either intelligence or evidence. Intelligence is used to support the investigation and provide information about the characteristics of the offender or events at the scene, but is not usually sufficient on its own to lead to an arrest or conviction [14,15]. Evidence may include an opinion on the findings or a factual conclusion and can be presented in a statement or in oral testimony to support an arrest or conviction. The National DNA Database and Ident1 fingerprint database in the UK allow for a named suspect to be established via an intelligence search and given as an evidential conclusion.

Forensic intelligence provided by footwear evidence can be considered to provide less compelling information regarding an offender's identity when compared with directly individualising traces such as DNA and fingerprint evidence. This is because footwear intelligence may suggest a list of potential suspects with further investigation and examination required to convert the intelligence to evidence, rather than naming one specific suspect [16]. Economic pressures and changing police priorities alongside this perception, as well as the issues in the way footwear is interpreted and reported, have contributed to the decision by some police forces to cease footwear examinations [17].

The Court of Appeal ruling [13] resulted in the publication of papers addressing the way footwear interpretation is undertaken [18–20]. There have been discussions concerning the Case Assessment and Interpretation model, which either include footwear evidence or discuss footwear exclusively [21–23]. Specific issues highlighted in the PCAST report (2016), such as whether or not damage on the sole of footwear can be shown to be unique [24,25] and methods to demonstrate reliability and consistency between examiners [26] have also been addressed.

Despite a broad range of published studies within the field of footwear examination, there is still a lack of a systematic approach that reviews and assesses the existing knowledge base in forensic footwear examination. Systematic reviews have been shown to be useful tools in healthcare, where they are used to assist with policy decisions and directing research to under-researched areas [27,28]. This approach is less common in forensic science [29] and, when reviews have been undertaken, they have rarely followed established guidelines, such as those published by the Cochrane Collaboration and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [30,31]. Systematic reviews in forensic science have generally focused on topics closely linked to medicine, such as forensic dentistry [32,33], but have also been undertaken in a number of other fields, including fingerprints [34], lip prints [35] and DNA [36], as well as in areas linked to the way in which forensic science is practised, such as research into cognitive bias [37] or misleading evidence [38].

This paper seeks to apply established guidelines for conducting a systematic review, to effectively review and assess the types of research that have addressed forensic footwear examination. Using this approach to map the landscape of the current existing research and identify opportunities for further work, it is hoped that it will be possible to identify where further research may resolve some of the issues impacting the use of footwear evidence in practice.

## 2. Method

This systematic review aims to categorise the research that has been undertaken in the field of forensic footwear examination and determine if the research to date meets the needs of practitioners and contributes to answering key questions to help their examination and evaluation of footwear cases as well as to identify any gaps in the literature that have not yet been addressed.

Subsequently, the insights generated from this systematic review will be compared with the main components of cases typically submitted to a forensic unit, by classifying submissions to the Lancashire Constabulary footwear unit for two separate years. It is hoped that this will identify areas where further research will support better intelligence, evaluation and interpretation by addressing pertinent issues encountered in the practice of forensic footwear examination.

Arguably, there is a lack of operationally useful research to identify the best method to evaluate correspondence and differences when interpreting footwear cases where the findings fall short of the practitioner being able to say that in their opinion the marks were made by the considered footwear and no other i.e. non-conclusive opinions: the so-called "grey areas". Therefore, the objective of this systematic review was also to evaluate the usefulness in practice of the current published research that addresses evidence recovery, examination and interpretation.

The review presented in this paper began with the establishment of a set of inclusion and exclusion criteria and the identification of appropriate keywords and representative databases. The results of searches of these databases were then screened and categorised and the results of the categorisation analysed to map the research undertaken in this field, together with the gaps. Finally, the research landscape was evaluated.

### 2.1. Criteria for considering studies for this review

The studies selected for this review addressed the forensic examination of footwear undersoles. Different aspects of forensic footwear examination were included to incorporate studies addressing recovery methods used by CSIs or scientists at crime scenes, photography and digital methods. Papers considering the examination of the marks or shoes, including the use of databases, AI and other tools for examination were also within scope. References which discussed specific characteristics of footwear, used to undertake comparison and evaluation of footwear with marks, including the pattern, size, wear and any damage (also referred to as Randomly Acquired Characteristics or RACs) were also included. Finally, studies were included which covered the interpretation of the findings of the examination including the use of methods such as a Bayesian approach, the use of Likelihood Ratios and communicating the conclusion using verbal or numeric scales. Other forms of forensic examination relating to feet and footwear, including podiatry, gait analysis, factors of footwear contributing to slips and accidents, and recovery of other forensic materials from footwear were not included as they were considered to be beyond the scope of this review.

The review considered both published and unpublished (grey) studies. However, books or chapters of books were excluded as the content of books and book chapters tends to include general information about methods available for footwear rather than research into techniques or concepts. Likewise, literature reviews, book reviews and associated general documents were excluded, due to referring to other already published studies and publications and thereby not introducing new concepts or research. Conference proceedings were included where a complete paper was available; where there was only a short precis or abstract of the content of the presentation, this was excluded. Finally, studies that were not published in or translated into English were excluded, as available resources limited the ability to search and translate studies in other languages. No date restrictions were applied but the final search was conducted on the 24th of November 2022.

The method for this study was developed in accordance with the

PRISMA Checklist and Abstract Checklist [39].

### 2.2. Searching terms

The search strategy for the systematic review was based on the Campbell Collaboration method [30].

A number of search terms were used in the electronic databases to identify studies of potential interest to the systematic review. An initial scoping review was undertaken to identify the keywords commonly associated with prominent papers that were already known to be within the scope of the review. Insights drawn from professional practice and from the literature itself were further used to decide on the best search terms to use to maximise the number of studies identified. The search terms relate to terms relevant to forensic footwear examination and were broken down into five main categories as shown in Table 1: Evidence, Recovery, Examination, Characteristics and Interpretation.

All searches included the search term *Forensic* AND the search terms in the category *Evidence* (*footwear* OR *"shoe print"* OR *"shoe mark"*). This was followed by the operator AND, with the search terms in each of the categories *Recovery, Examination, Characteristics* and *Interpretation* following, separated by the operator OR. For example, for the category *Recovery,* the following search was launched:

> forensic AND (footwear OR "shoe print" OR "shoe mark") AND (enhancement OR latent OR casting OR trace OR recovery)

Due to the number of terms in the category *Characteristics*, this was split into two sections – one included the search terms *"randomly acquired characteristics"* OR *RACS* OR *pattern* OR *wear* and the other included the search terms *damage* OR *features.* Full details of all of the searches undertaken are provided in Appendix A.

### 2.3. Searching for and identifying studies

Four electronic databases were searched using the search terms described in Section 2.2: Pubmed, Scopus, Science Direct and Web of Science. The review was managed using EPPI-Reviewer Web [40]; this is a web-based program designed specifically to facilitate systematic reviews and enable management and classification of papers. Search results were uploaded into EPPI-Reviewer, which in most cases uploads the title and abstract of the study, as well as information about the authors, journal and dates of publication. Furthermore, if the abstract was not included in the upload or did not contain sufficient information to make a decision on whether or not to include a study, the study was accessed either via the electronic database from which it was identified, from the university's online library or from elsewhere on the internet.

### 2.4. Screening of results on title and abstract

Once the searches above had been conducted in each of the four electronic databases and the results uploaded into EPPI-Reviewer, the studies were first scanned for duplicate studies, using software in the EPPI-Reviewer system. Following this, the remaining studies were screened on title and abstract against a number of inclusion and exclusion criteria.Those studies that were excluded were considered to be inappropriate for the review for a number of reasons:

1. The study did not relate to forensic comparison of footwear undersoles – for example, many of those articles identified related to research into areas such as podiatry, gait or slips and falls; to bare footprints rather than marks made by footwear; or to the recovery of other evidence, such as blood or particulates, from footwear
2. The type of article – as stated above, books, chapters, literature reviews, book reviews and associated general documents were omitted
3. The study was not in English

Despite EPPI-Reviewer including a function to search for duplicate references, there were still some duplicates in the papers identified for screening. On further investigation, it appeared that this was a result of two similar papers, with a number of occurrences of each, being identified as a single duplicate by EPPI-Reviewer. The papers which matched the first paper were marked as a duplicate but those that matched the second paper were not a duplicate of the first paper and were therefore not marked as such by the reviewer. However, these papers were duplicates of each other, but were not subsequently identified in automated duplicate searches and were therefore included in the papers for screening. Therefore, an additional exclusion category was added:

4. The study was a duplicate (not identified by EPPI-Reviewer)

Only one exclusion reason was allocated to a study and priority was given first to the study being a duplicate (if not identified by EPPI-Reviewer) and secondly to the study not relating to forensic comparison of footwear undersoles.

### 2.5. Inter-rater reliability

As the searching, coding and screening were undertaken by one rater, the reliability of the coding was studied by a second person coding a sample of the studies screened on Title and Abstract. Following the initial searches described in Section 2.3, 2478 studies had been identified after duplicates were removed. The second rater was given a sample of 248 studies (10 % of the references) and coded these blindly, i.e. without knowledge of the code allocated by the first coder. The initial results of the inter-rater reliability assessment appeared to show an apparent issue, with only 145 codes showing agreement with the first code, equating to 58 % and 103 showing disagreement, equating to 42 %.

The papers where there was disagreement were each reviewed to identify the differences and aim to determine whether there was a major issue with the methodology or if there was a more straightforward reason, such as the instructions given to the second rater. On further comparison of the coding by the first and second rater, it was clear that the main reason for the differences was due to incomplete or misleading instructions given to the second rater.

The most frequently observed disagreement in coding was due to the first rater prioritising exclusion due to the study not being related to footwear comparison over other exclusion reasons. There were 50 studies where the first rater had excluded for this reason, but the second rater had excluded due to the type of article, which, although a correct exclusion, was over-ridden by the subject matter. It had not been clear in the instructions that the exclusion category of the paper not being related to footwear comparison should be prioritised over other reasons.

Furthermore, as well as prioritising exclusion due to the study not being related to footwear comparison, the first rater only excluded based on one reason, whereas the second rater was not aware of this and had excluded for two reasons in 25 studies; in all of these cases, the exclusion reason given by the first rater was one of the two given by the second

**Table 1**
Search terms used to identify records of potential interest to the systematic review.

| Evidence | Recovery | Examination | Characteristics | Interpretation |
|---|---|---|---|---|
| Footwear | Enhancement | Database | Randomly Acquired Characteristics | Bayes |
| Shoe Print | Latent | Automatic | RACs | Likelihood |
| Shoe mark | Casting | Identification | Pattern | Probability |
| | Trace Recovery | Intelligence Coding | Wear Features Damage | Interpretation Scale |

rater.

There was also one study, which occurred three times in the sample, where the first rater had excluded on only one reason. The second rater had also excluded but had given two reasons, neither of which correlated with the reason given by the first rater. On review, all of the exclusion reasons given by both raters were valid for this reference, which was ultimately excluded twice as a duplicate and once as not being related to footwear comparison. The first rater also advised the second rater to exclude conference proceedings but did not make it clear that where a full paper was available this should be included. A total of 5 studies fell into this category and were ultimately included. Ten papers had been excluded by the first rater as duplicates but had not been identified as such by the second rater; this was due to only one occurrence of the paper being in the sample that the second rater had access to. Finally, three papers had been classified to Include for Second Opinion by one rater and to Include on Title and Abstract by the other rater. As both raters had included these papers, they were all updated to Include on Title and Abstract.

This accounted for 96 of the 103 studies with apparent disagreement, leaving only 7 cases where there was actual disagreement, equating to 3 % or 97 % agreement and indicating reliability of the method and coding, with the issue being lack of clear instructions to the second rater. The remaining 7 cases were reviewed; for five of the studies the first rater had included the paper, but the second rater had excluded and vice versa for the remaining two. The papers and decisions were reviewed: for five of the papers, the original coding was retained but for two of the papers the coding was changed to the second rater's decision.

### 2.6. Breakdown of studies

Initially 8813 studies were uploaded to EPPI-Reviewer following the searches detailed above. An automated tool in the EPPI-Reviewer software was used to identify duplicates, which reduced the number of papers to 2478. These were then screened on title and abstract using the above inclusion and exclusion criteria, resulting in the inclusion of 303 studies.

Backwards and forwards citation searches were then conducted on the included studies. Each study cited within the included studies was identified as well as any studies which cited the included studies. The backwards and forwards citation searches were collated in Excel in order not to import numerous additional and potentially irrelevant studies into EPPI-Reviewer. Studies found in this way were then reviewed to find those which were not already included in EPPI-Reviewer and appeared to meet the criteria for inclusion based on title alone. A further 269 studies were identified and uploaded to EPPI-Reviewer, where they were scanned to identify duplicates and then screened against the same criteria, leading to inclusion or exclusion. Backwards and forwards citation searches were then conducted on the additional included studies, until no additional papers were identified.

Finally, the searches were relaunched on the 24th of November 2022 for papers published in 2022 to identify any studies which were not available when the original searches were conducted. This resulted in a further 266 studies being imported to EPPI-Reviewer. However, only 3 were new papers not already within the review, which met the inclusion criteria. A backwards and forwards citation search of the 3 papers found no further studies.

Overall, a total of 9347 studies were imported into EPPI-Reviewer, 6620 of which were identified as duplicates by the software. Following screening on title and abstract, the number of studies included was 489. A full breakdown of studies included and excluded at each stage of the review is shown in Fig. 1. This diagram has been adapted from the PRISMA flow diagram included in the reporting guideline [39] to include features of this systematic review including backwards and forwards citations which are not covered by the PRISMA flow diagram.

### 2.7. Categories and Sub-categories

Once the final set of records which were deemed relevant and appropriate to the systematic review had been identified by screening on title and abstract, the full text of the included studies was accessed, where available. The studies were again assessed against the above criteria to determine whether or not they were relevant for the full systematic review. Those studies which were included were classified on EPPI-Reviewer by their thematic content using the following categories: *Recovery*, *Examination*, *Characteristics* and *Interpretation*. An Excel spreadsheet was used to list each study assigned to the categories and further classify them using sub-categories (Table 2). A brief description of each study was also recorded. There were a number of studies,

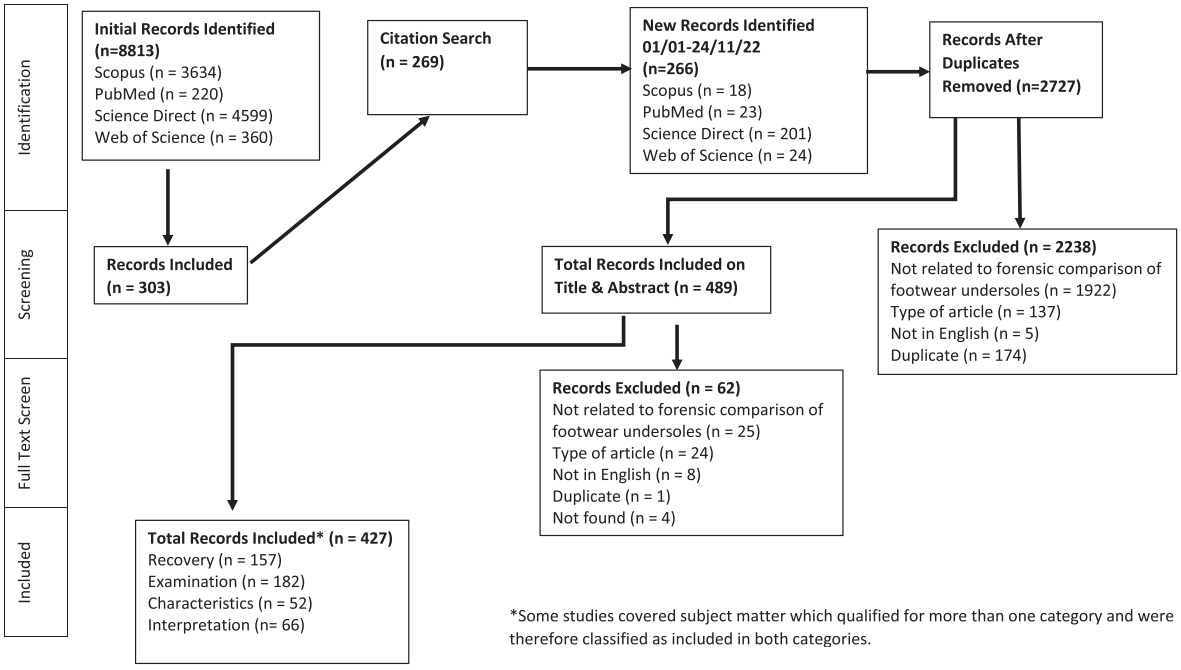


**Fig. 1.** Breakdown of studies identified in literature search.

**Table 2**
Categories and sub-categories used to classify records identified in the systematic review.

| | |
|---|---|
| **RECOVERY** | Blood & chemical enhancement |
| | Casting |
| | Chemical enhancement - other |
| | ESLA |
| | Gel lift |
| | Photography |
| | Powder |
| | Other |
| **EXAMINATION** | Algorithm |
| | Comparison |
| | Database |
| | Intelligence |
| | Print coding |
| | Scene coding |
| | Scene linking |
| | Test marks |
| **CHARACTERISTICS** | Pattern |
| | Size |
| | Wear |
| | Damage |
| **INTERPRETATION** | General interpretation |
| | Interpretation of damage |
| | Non-conclusive |
| | Pattern frequency |
| | R-v-T |
| | Scale |

(n=65), for which the full paper could not be accessed. Where the content was evident from the title or abstract (where available), these papers were still included and classified. There were also a number of studies, (n=61), which had been included on Title and Abstract but were determined to be excluded when the full paper was accessed, including four of those not found.

It should also be noted that there were a number of papers that reported the same research or study but were not strictly speaking duplicates as they were published in a different journal, in a different format, included somewhat different findings or cited different authors. These papers were not coded as duplicates but were instead included in the review.

## 3. Results

As described, the included papers were classified into four categories and sub-categorised within these categories (Table 3). Some studies covered subject matter which qualified for more than one category and were therefore classified as included in both categories. This resulted in the sum of papers in each category being higher than the overall total of included papers. The proportion of papers in each category is shown in Fig. 2. The number and proportion of papers in each category and sub-category are shown in Table 3 and Fig. 3.

The first category was *Recovery* which relates to the recovery and enhancement of marks from scenes. The second was *Examination* which incorporates studies discussing the analysis, comparison or classification of footwear marks once they have been recorded or recovered. Third was *Characteristics,* relating to specific class or identifying characteristics of a footwear mark. Finally, the fourth category was *Interpretation*.

### 3.1. Recovery

Of the 427 papers included after screening on full text, 157 (36.7 %) relate to the recovery of footwear marks. This category included the recovery and enhancement of marks from scenes, with sub-categories defined as *blood & chemical enhancement* [41–65], *casting* [66–96], *chemical enhancement – other* [97–120], *ESLA* [121–134], *gel lift* [135–139], *photography* [79,81,140–164], *powder* [165] and *other* [166–195]. Studies relating to the recovery of footwear scene marks

**Table 3**
Numbers of papers in each category & sub-category.

| Category | Papers Included | Percentage | Ref. |
|---|---|---|---|
| **RECOVERY:** | **157** | **36.7 %** | |
| Blood & Chemical Enhancement | 25 | 5.9 % | [41–65] |
| Casting | 31 | 7.3 % | [66–96] |
| Chemical Enhancement – Other | 24 | 5.6 % | [97–120] |
| ESLA | 14 | 3.3 % | [121–134] |
| Gel Lift | 5 | 1.2 % | [135–139] |
| Photography | 27 | 6.3 % | [79,81,140–164] |
| Powder | 1 | 0.2 % | [165] |
| Other | 30 | 7 % | [166–195] |
| **EXAMINATION:** | **182** | **42.6 %** | |
| Algorithm | 107 | 25.1 % | [196–302] |
| Comparison | 23 | 5.4 % | [163,177,188,303–322] |
| Database | 28 | 6.6 % | [323–350] |
| Intelligence | 9 | 2.1 % | [16,351–358] |
| Print Coding | 0 | 0 % | |
| Scene Coding | 5 | 1.2 % | [359–363] |
| Scene Linking | 3 | 0.7 % | [364–366] |
| Test Marks | 7 | 1.6 % | [367–373] |
| **CHARACTERISTICS:** | **52** | **12.2 %** | |
| Pattern | 12 | 2.8 % | [374–385] |
| Size | 1 | 0.2 % | [386] |
| Wear | 13 | 3 % | [218,219,329,387–396] |
| Damage | 26 | 6.1 % | [23,25,167,313,367, 397–417] |
| **INTERPRETATION:** | **66** | **15.5 %** | |
| Conclusive | 2 | 0.5 % | [418,419] |
| General Interpretation | 25 | 5.9 % | [2,26,177,311,321,322, 414,420–437] |
| Interpretation of Damage | 17 | 4 % | [23,24,167,313,399,400, 402,405,409–411,414, 415,417,438–440] |
| Non-conclusive | 5 | 1.2 % | [387,441–444] |
| Pattern Frequency | 3 | 0.7 % | [335,336,374] |
| R v T | 10 | 2.3 % | [18–20,445–451] |
| Scale | 4 | 0.9 % | [9,452–454] |

were fairly evenly distributed across this category, although there were more papers relating to blood & chemical enhancement (n=25), casting (n=31) and photography (n=27), with only small numbers relating to gel lifting (n=5) and the use of powders (n=1).

### 3.2. Examination

The highest proportion of papers, 182 (42.6 %), relate to the examination of footwear undersoles. Papers in this category were sub-categorised as *Algorithm* (to include computerised systems generally) [196–302], *Comparison* (i.e. between crime scene marks and shoes or prints) [163,177,188,303–322], *Database* [323–350], *Intelligence* [16, 351–358], *Print Coding* (no papers identified), *Scene Coding* [359–363], *Scene Linking* [364–366] and *Test Marks* [367–373].

By far the highest number of papers observed covered the use of computer algorithms for the examination of footwear marks. This was the largest number of papers in any sub-category of the review, comprising 25.1 % (n=107) of all papers included. Most of these papers propose different algorithms to identify the pattern of footwear from a database of classified prints. A number of different methods were used and the parameters were varied, including papers which attempted to classify marks which were partial, distorted or included artefacts and noise in the image [202,204,213,226].

The sub-category *Database* included 28 papers, which was approximately 6.6 % of all the results in the review. This included papers relating to the creation of a database to facilitate the identification of footwear patterns where the coding was still undertaken manually or only semi-automatically, i.e. without the use of an algorithm [323,324, 327,340,342], as well as papers considering different databases in use

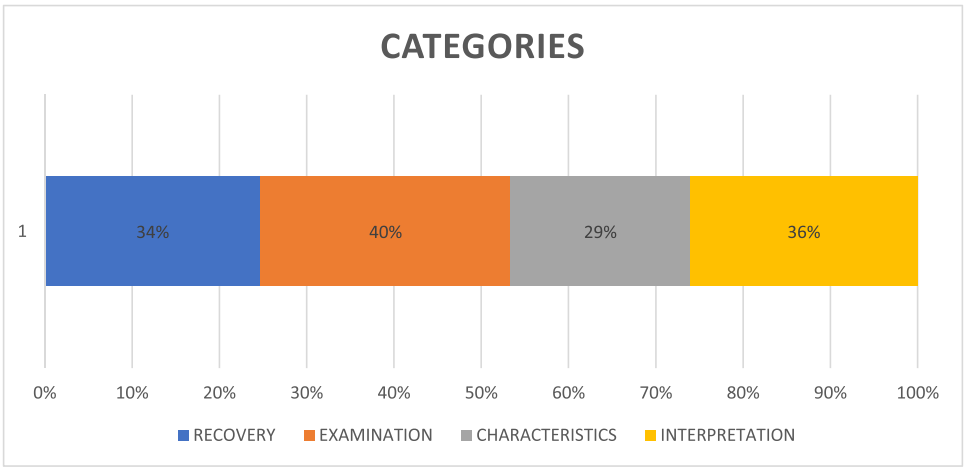


**Fig. 2.** Proportion of papers classified into each of the four categories *Recovery, Examination, Characteristics* and *Interpretation*. NB: Some papers were included in more than one category therefore the sum of papers in each category is higher than the overall total of included papers.

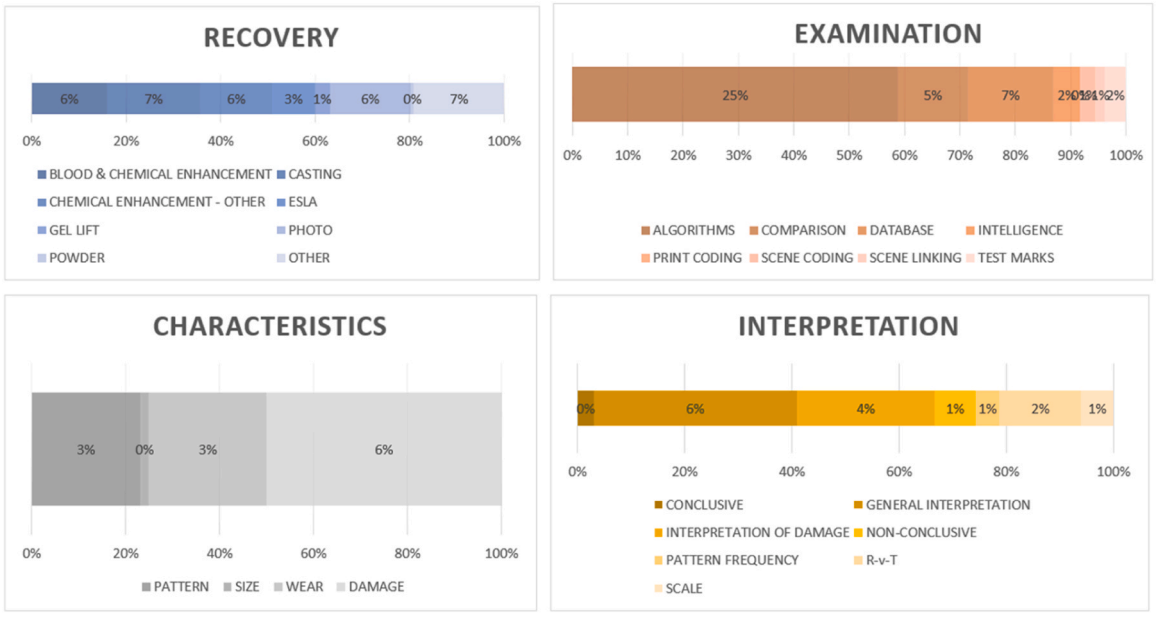


**Fig. 3.** Proportion of papers classified into each of the sub-categories within the categories *Recovery, Examination, Characteristics* and *Interpretation*.

[325,345,349] and databases for validation [348] or to provide statistical data to inform decisions on pattern frequency [348]. The papers referred to benefits of using databases, including increased identification of offenders and better understanding of the use and benefits of the use of footwear [323,324,328,343]. There was recognition of the need for the reference examples in the database to be good quality [325] and of sufficient and relevant training [324].

There were 23 papers coded in the sub-category *Comparison* [163, 177,188,303–322]. These papers included studies of the methods used by practitioners to compare questioned footwear marks from crime scenes with known footwear from suspects or others [312,313], including studies of the decision-making process [321,322]. It also included case studies [304,309,318] where the method used to compare the scene marks and footwear were documented and descriptions of methods to facilitate the comparison or presentation of the evidence, such as imaging software [188,305,308]. Three papers included in this sub-category considered the role of the footwear examiner and the required skills or training [177,306,310].

Only 24 papers were classified as studies in the areas of *Intelligence* (n=9) [16,351–358], *Scene Coding* (n=5) [359–363], *Scene Linking* (n=3) [364–366] and *Test Marks* (n=7) [367–373]; no papers were classified in the sub-category *Print Coding*. Clearly, some of the papers that were included in the sub-categories *Algorithm* or *Database* also cover some aspects of intelligence, scene coding, print coding and scene linking. However, the papers where the main subject of the study was the design and testing of the algorithm or database were included in those categories; those papers which specifically discussed the issues, benefits or outcomes of intelligence, coding and linking activities were included in those categories.

### 3.3. Characteristics

Only 52 papers (12.2 %) were classified in this category. These papers were sub-categorised as *Pattern* [374–385], *Size* [386], *Wear* [218, 219,329,387–396] and *Damage* [218,219,329,387–396], which are the categories of characteristic used within footwear examination [1]. Nearly half of the papers in the category *Characteristics* were concerned with damage or randomly acquired characteristics (n=26). Many of

these papers propose methods to quantitatively evaluate the significance of randomly acquired characteristics [23,399,408,415], determining how random their occurrence is [25,397,400–402] and indeed whether or not they can be determined to be unique [313,409]. Only one paper [386] was identified which discussed the property of size in footwear marks: this considered how to determine the full shoe length from a partial mark. No studies were identified which discussed the variation of footwear undersoles within and between sizes or considered the empirical value of this when undertaking an examination. Studies had been undertaken on both pattern [374–385] and wear [218,219,329, 387–396] variations, but there was still significantly less research in these areas (n=12 and n=13 respectively) than for randomly acquired characteristics. In relation to wear, research was particularly concerned with "feathering" or Shallamach features on rubber-soled footwear [388,389,392,393,396].

### 3.4. Interpretation

Finally, 66 papers (15.5 %), relate to the interpretation of footwear evidence, and were classified in sub-categories defined as *Conclusive* [418,419], *General Interpretation* [2,26,177,311,321,322,414,420–437], *Interpretation of Damage* [23,24,167,313,399,400,402,405,409–411, 414,415,417,438–440], *Non-conclusive* [387,441–444], *Pattern Frequency* [335,336,374], *R v T* [18–20,445–451] and *Scale* [9,452–454]. The majority of the papers in this category (n=25) were general overviews of interpretation [2,26,177,311,321,322,414,420–437], which includes studies to determine the consistency of the interpretation and opinion of different experts [26,414,425,427–431], as well as considerations of factors such as bias and fatigue in the decision-making process [321,322,432]; a number of these papers were also included in the sub-category *Comparison* in the category *Examination* [177,311,321, 322]. Seventeen (4 %) of those papers included related to the interpretation of damage features with a further 2 (0.5 %) dealing with conclusive findings. Ten papers (2.3 %) discussed the R v T UK appeal court ruling [13]. Only a small number of papers, 5 (1.2 %), dealt with the interpretation of non-conclusive cases other than in the context of the R v T ruling.

## 4. Discussion

The aim of this systematic review was to categorise research in the field of forensic footwear examination, determine if it met the operational needs of practitioners and identify gaps in the research which would benefit the discipline. The systematic review was undertaken using a search strategy based on the Campbell Collaboration method [30]. Searches, using sets of appropriate keywords (Table 1), were conducted of four databases and collated using EPPI-Reviewer Web [40]. The papers were screened, first on title and abstract and then on full text and categorised as shown in Tables 2 and 3.

Whilst the 427 papers included in the systematic review demonstrated a broad spread of research across the subject of forensic footwear examination, there was a marked prevalence of papers which fell into the categories *Recovery* and *Examination*, with fewer papers relating either to *Characteristics* or *Interpretation*.

Within the category *Recovery,* the majority of studies in the systematic review considered the use of casting (n=31) [73,77], photography (n=27) [141,155] or blood & chemical enhancement (n=25) [43,57]. It is likely that this is due to a number of factors. For example, the research may reflect those marks which are most difficult to record, such as marks which require enhancement or 3D impressions which need to be cast. In addition, the research may focus on those techniques where there has been the most advancement in technology, such as imaging or alternatively, the research may be seen to be of most value for those impressions where the risk is highest, particularly those relating to major or serious crime, such as marks in blood [43]. It is suggested that there may be a gap in the research relating to methods more routinely used in the investigation of volume crime offences, such as burglaries or robberies, such as ESLA, gel lifting and powdering. However, further understanding of whether this research would improve the use of these techniques is required.

Of all the studies included in this systematic review, the largest subcategory (n=107) was those which considered the development or use of algorithms for automatically coding footwear marks. However, the majority of footwear mark coding in the UK is still undertaken manually by a practitioner [17]. An automated system for coding prints taken from the footwear of prisoners when in custody, TreadMatch [368] which works with the National Footwear Database (NFD), is in use in some, but not all, police forces. This low uptake of automated methods suggests that despite the extent of research in this area, forensic units are not implementing the developed methods. This may be for a number or reasons: a) forensic units do not have the budget to invest in new technology; b) the methods developed are not being promoted to footwear practitioners; c) the software does not link with current systems, such as the NFD; d) the technology requires further research or validation; or e) the method does not deliver the suggested benefits. It has often been reported that there is a breakdown between research in forensic science and its implementation in operational forensic units due to a lack of communication or collaboration [455], which may suggest that practitioners may simply be unaware of the existence of these solutions, although it is probably a combination of all of the above reasons.

There were only small numbers of papers in each of the categories relating to intelligence (n=9) [351,354], scene linking (n=3) [364] and patten coding (n=5) [360]. This demonstrates that, with the exception of the glut of research on the creation of an automated pattern identification system, there is a gap in the available research in the area of footwear intelligence. This may be an area of forensic science that is overlooked or undervalued, possibly due to the fact that, unlike DNA or fingerprint intelligence, it rarely provides a name of a suspect. It is believed that further research into the outcomes and value of footwear intelligence would be useful to determine whether this is an area which is worth investing in. The proliferation of studies into AI methods to facilitate this suggest there is an appetite to undertake this activity but that it needs to be streamlined and less time-intensive to be seen as worthwhile; however, the low uptake of these systems, certainly in the UK, suggests that there is still some way to go to resolve this issue.

The smallest number of papers (n=52) were identified in the category of *Characteristics*; studies in this category were dominated by research into damage or randomly acquired characteristics (n=26) [397, 408]. This concentrated focus may be a result of the PCAST report [10], which specifically mentions the need for the empirical study of randomly acquired characteristics. Many of these papers propose methods to quantitatively evaluate the significance of randomly acquired characteristics, determining how random their occurrence is and indeed whether or not they can be determined to be unique [397,408]. Whilst this is undoubtedly interesting research, the lower prevalence of research into similar aspects of other characteristics is a notable gap in the research. Clearly the quantitative or statistical significance of randomly acquired characteristics can only be of relevance within the context of the evaluation of the footwear comparison overall, requiring similar understanding of the quantitative or statistical significance of pattern frequency, size and configuration, and the degree and distribution of wear. Only one paper [386] was identified which discussed the property of size in footwear marks: this considered how to determine the full shoe length from a partial mark. No studies were identified which discussed the variation of footwear undersoles within and between sizes or considered the empirical value of this when undertaking an examination. Studies had been undertaken on both pattern and wear variations [375,381,390], but there was still significantly less research in these areas (n=12 and n=13 respectively) than for randomly acquired characteristics. In relation to wear, research was particularly concerned with "feathering" or Shallamach features on rubber-soled footwear [389,392,393]. This demonstrates a gap in the current research relating

to three of the four characteristics considered during footwear comparisons. There are few studies to evaluate these properties and provide usable data about their occurrence, variation or persistence which would support the work of operational footwear practitioners.

The final category was *Interpretation*; again this included fewer papers (n=66) than the first two categories, with the majority of studies in this category concerned with general interpretation (n=25) [444,456]. Many of the papers within this category also considered the interpretation of damage (n=17) or discussions of the provision of a "conclusive" result (n=2) [418,438], with far fewer considering those comparisons where randomly acquired characteristics are not present (n=5) [441,444].

The footwear comparison in the R v T case [13] fell into this category and several papers (n=10) were included which discussed the UK appeal court ruling for this case [445,451,457]; the ruling was issued in 2011 and all of the papers included in this sub-category were published in 2011 and 2012, demonstrating a flurry of interest that is to be expected following a judgment on a forensic issue, but likewise suggesting that interest in this area of footwear interpretation soon died down. Nevertheless, this case highlighted some significant weaknesses and issues with footwear interpretation which have not been resolved and which may be replicated in other forensic fields.

The final database searches for studies to be considered in this systematic review was the 24th of November 2022. A systematic review is, by nature, a snapshot in time and new studies will inevitably be published after the review has been concluded. Nevertheless, in order to consider additional studies published between the completion of the review and the submission of the paper for publication, a repeat of all searches was undertaken on the 4th of October 2024.

Initially, this resulted in 1087 papers being identified in the four databases used and with the same search strings used. These papers were screened on title only to identify duplicates and exclude studies for the reasons defined in Section 2.4: the study did not relate to forensic comparison of footwear undersoles, the type of article or the study was not in English. This reduced the papers to be considered to 37 papers, of which 11 were found to have already been included in the review. This left 26 papers that were not already in the review. These were screened further, considering the title and abstract and, if necessary, the full paper. From this further screen 2 papers were excluded on the type of article; both related to conference proceedings. Seven studies were excluded as they did not relate to the forensic comparison of footwear undersoles. The remaining 17 papers would be included and were subcategorised as follows: 3 papers related to Recovery [458–460], 7 related to examination [461–467], 3 related to characteristics [468–470] and 4 related to interpretation [471–474].

We took the careful decision not to incorporate these additional 17 papers into the systematic review. To do so would change the parameters of the study, and in effect require the study to be undertaken all over again. We believe that given the relatively small number of additional papers that have been published in the last 21 months that the value of the review remains intact and offers valuable insight.

Further research into the area of footwear interpretation and the use of reference data and pattern frequency information to support transparent interpretation would be of benefit to practitioners on a day-to-day basis, providing a more robust and consistent method to evaluate footwear evidence, leading to better agreement between practitioners and therefore an improved degree of reliability and trust in the field. Anecdotally, many footwear cases fall into this "grey area" where there is not enough detail to provide a high level of support for the view that the mark was made by the considered footwear but where the footwear cannot be excluded as the source of the mark.

## 5. Conclusions

This systematic review considered papers published in journals, as part of theses and dissertations and presented at conferences where details of the content were available. It identified that overall, there is a significant body of research that has been undertaken addressing forensic footwear examination. Nevertheless, gaps were identified in the body of published research in a number of key areas.

First, more research addressing the use of footwear intelligence, including pattern and scene coding and establishing the benefits of scene linking would assist with demonstrating the value of forensic intelligence and inform decisions on whether to invest in this area of work. Currently the bulk of papers published in this area demonstrate a prevalence of research to design an automated system to code footwear marks. However, the majority of these methods have not been implemented operationally, indicating that the benefit of this area of work must first be established before significant investment in new technology can be made.

Second, research into the properties of footwear prints that are considered by footwear practitioners when undertaking the analysis, comparison and evaluation of footwear marks, such as pattern frequency, size variation and the way in which wear develops on footwear undersoles would be of benefit and facilitate the interpretation of footwear comparisons where there is limited detail and a lack of randomly acquired characteristics which produce stronger or categorical conclusions.

Third, a robust, transparent and consistent method to determine and express the significance of a footwear comparison which would enable practitioners to communicate in a clear and unambiguous manner the weight of their findings would be of benefit not just to practitioners, but also to the courts and the Criminal Justice System as a whole. Ideally, such a method would serve to evaluate comparisons where there is good detail and a wealth of information, but also and particularly those comparisons where there is limited detail or increased uncertainty to the degree to which the correspondence is significant.

## Declaration of Competing Interest

A portion of this research is part of a PhD research project but none of the work submitted in this manuscript has been previously published.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. search strings used for systematic review searches

forensic AND (footwear OR "shoe print" OR "shoe mark") AND (enhancement OR latent OR casting OR trace OR recovery)

forensic AND (footwear OR "shoe print" OR "shoe mark") AND (database OR automatic OR identification OR intelligence OR coding)

forensic AND (footwear OR "shoe print" OR "shoe mark") AND ("randomly acquired characteristics" OR RACs OR pattern OR wear)

forensic AND (footwear OR "shoe print" OR "shoe mark") AND (damage OR features)

forensic AND (footwear OR "shoe print" OR "shoe mark") AND (Bayes OR Likelihood OR probability OR interpretation OR scale)

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