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The evaluation of fingermarks given activity level propositions

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ABSTRACT

Fingermarks are highly relevant in criminal investigations for individualization purposes. In some cases, the question in court changes from 'Who is the source of the fingermarks?' to 'How did the fingermark end up on the surface?'. In this paper, we explore the evaluation of fingermarks given activity level propositions by using Bayesian networks. The variables that provide information on activity level questions for fingermarks are identified and their current state of knowledge with regards to fingermarks is discussed. We identified the variables transfer, persistency, recovery, background fingermarks, location of the fingermarks, direction of the fingermarks, the area of friction ridge skin that left the mark and pressure distortions as variables that may provide information on how a fingermark ended up on a surface. Using three case examples, we show how Bayesian networks can be used for the evaluation of fingermarks given activity level propositions.

1. Introduction

Fingermarks play an important role in forensic science. Based on the assumption that every individual holds a unique pattern of friction ridge skin on their hands, this pattern can be used for identification. By determining the source of the fingermark, a link between the donor and a crime scene can be established. There is a wealth of research on the visualization of latent fingerprints in order to enhance the friction ridge pattern for individualization purposes [1,2]. While this type of research is very valuable for the individualization of the source of a trace, the fingermark itself may not unequivocally be attributed to a criminal activity.

An important question that often comes up in court cases regarding forensic evidence is to determine how or when a trace was deposited. Consider the following case example; a woman calls the police to report that there has been a burglary in her apartment. The police find four fingermarks on the railing of the balcony, which leads to the assumption that the perpetrator entered the apartment via the balcony. Through a database search, a match is found with a suspect, who is an acquaintance of the woman. The suspect claims that, instead of an unauthorized intrusion via the balcony, he visited the woman a week earlier and smoked a cigarette on the balcony while leaning on the railing. In cases like this, the question at stake changes from 'Who is the source of the fingermarks?' to 'What activity led to the deposition of the fingermarks?', which requires a different assessment of the findings.

When investigating forensic evidence, a forensic scientist formulates a set of propositions, usually representing the prosecution and the defense propositions. Cook, Evett, Jackson, Jones and Lambert [3] propose three classes of propositions: source level, activity level and offence level propositions. In the balcony case example, the investigation shifts from determining the source of the fingermarks to addressing the activity that took place. In the forensic expertise fields of DNA, fibres, glass, paint and gunshot residues, evaluation of the evidence given activity level propositions is already being studied [4]. However, for fingermarks, this topic is not yet explored.

There are many variables that may provide information on how a fingermark was deposited on a surface. In the balcony case example, where the question now is whether the suspect climbed the balcony or the suspect smoked a cigarette on the balcony and leaned on the railing, variables such as the location of the fingermarks, and the direction of the fingermarks may provide information on the activity that took place. In general, the interpretation of evidence at activity level requires more contextual information [3]. When multiple variables

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influence the interpretation of the evidence, it can be difficult to take their dependencies into account in a direct calculation of a likelihood ratio [5].

A method that is commonly used for cases where additional factors play a role is a Bayesian network. A Bayesian network is a graphical representation of a mathematical model which can be used to evaluate the findings, particularly if there is a dependency between relevant variables [4]. A Bayesian network consists of nodes, directed arcs and probability assignments of the nodes. It can for instance be used to compute a likelihood ratio of the evidence given the prosecution proposition and the defense proposition, based on all variables that are considered relevant in the interpretation of the evidence. This makes Bayesian networks an appropriate method to evaluate evidence given propositions at activity level within the field of forensic science. Although Bayesian networks have been proposed to interpret fingermarks given source level propositions [6], they have not been used to evaluate fingermarks given activity level propositions.

In this paper, we describe a framework for the evaluation of fingermarks given activity level propositions using Bayesian networks. We discuss the variables that provide information on fingermarks at activity level, followed by three case examples for which Bayesian networks are created. We ultimately elaborate on possible directions for further research on this topic such that the proposed framework could be optimally applied in casework.

2. Relevant variables

In this section, we explore the variables that provide information on fingermarks with regards to activity level propositions. We do not discuss variables related to source level propositions since determining the donor of a fingermark is considered outside the scope of this study. Furthermore, we assumed that if a fingermark is present, the donor actually touched the item.[1] Touching a surface can be seen as an activity in itself, and therefore activity level propositions may dispute whether the surface is actually touched or the fingermark is a result of forgery [1]. Another dispute may focus on the circumstances of how the fingermark is recovered, for instance when there are issues with the chain of custody [7]. These types of propositions are considered outside the scope of this paper by assuming the surface is actually touched when a fingermark is present.

We divided the relevant events that provide information on the activity that led to deposition of the fingermarks in two groups of variables: 'fingermark formation process', and 'manner of deposition'. The group 'fingermark formation process' represents the factors that relate to the requirements of fingermark formation, visualization and recovery. The variables identified in this group are the transfer, persistence and recovery of fingermarks and the background levels of fingermarks already present on an item. The group 'manner of deposition' represents the factors that relate to how the donor deposited the fingermark. The variables identified in this group are the position of the hand during placement, the location of the fingermarks, area of friction ridge skin that left the mark, the direction of the fingermarks and the pressure applied to the surface during deposition.

2.1. Fingermark formation process

2.1.1. Transfer

A consequence of an activity may be the transfer of material to a surface by a finger, creating a fingermark. Until now, research on the transfer of fingermarks focused mostly on the composition of the residue for the purpose of enhancing the quality of the fingermark for individualization at source level [8]. However, the guidelines of the ENFSI [9] show that transfer is an important variable to consider when looking at the scientific findings in relation to activities.

Fingermarks have advantages over other types of forensic evidence. Fingermarks are considered to be a proof of contact due to a direct transfer of the ridge detail to a surface. Furthermore, fingermarks cannot transfer indirectly via surfaces or individuals unless great effort is made [10]. Secondary or further transfer of fingermarks is generally not taken into account (please note the exception of fingermarks on tape [11]). These are important advantages over DNA, since DNA can transfer indirectly and even retransfer from one location to another [12]. Although indirect transfer is generally not applicable to fingermarks, transfer is still an important variable to consider since the probability of transfer of a fingermark may differ between activities.

The transfer of fingermarks depends on several factors: the nature of the surface, the deposition conditions and donor characteristics [8,13,14]. The deposition conditions such as pressure and duration of contact may vary between activities, and this may result in different transfer probabilities. If the pressure of the hand on the surface is higher, the probability of transfer might be higher [13]. The propositions of the prosecution and the defense may suggest different levels of pressure needed to conduct the proposed activities, leading to the assignment of different transfer probabilities. This is also true for other deposition conditions, which make the observed transfer (or the absence thereof) more or less probable given different propositions. However, the development and recovery of fingermarks on a surface depend on more than the mechanisms of transfer; variables such as persistence and recovery also influence the probability of recovering fingermarks.

2.1.2. Persistence

A fingermark may not be recovered in the same condition as it was deposited. This is due to degradation, the process during which the initial composition of a fingermark changes after deposition [8]. Degradation will occur from the time the fingermark has been deposited, to the subsequent evidence recovery and may affect the persistence of a fingermark. The degradation of a fingermark is influenced by the 'triangle of interaction', consisting of the fingermark composition, the nature of the surface and environmental conditions [2]. For the nature of the surface it is known that fingermark compounds may be absorbed by surfaces of porous material, whereas they stay on the surface of non-porous materials. This surface interaction may influence the degradation of the fingermarks [15]. Furthermore, environmental factors like temperature, light, humidity and air circulation have shown to influence the degradation of fingermarks over time [14].

It is generally not expected that the nature of the surface is disputed between activity level propositions since the same set of fingermarks on the same item is questioned under both propositions (unless there is an issue with the chain-of-custody [7]). However, environmental conditions may vary between a pair of activity level propositions for fingermarks, for example, if propositions dispute the moment when the fingermark is left and thus the time interval between the moment of deposition and recovery. During that time interval, the fingermarks could be subjected to different environmental conditions. In that case, the factor persistence plays a significant role.

2.1.3. Recovery

After transfer to and persistence on a surface, the fingermark must be detected and recovered from the crime scene. This process

[1] On a crime scene, fingermarks can be found on items and fixed surfaces. In this article, we use the term item for both, unless further specified.

is described by the variable recovery. Fingermarks can be latent, meaning that they must be visualized with the use of an enhancement technique. Several factors influence the success rate of the detection of a fingermark. The sensitivity of the available methods to visualize fingermarks varies [16], meaning that not every technique has the same success rate. Furthermore, an incorrect choice of technique, an incorrect application of a technique or applying multiple techniques in the wrong order can result in lower success rates of finding a fingermark [17]. Another factor influencing the recovery probability is targeting of the correct location. Fingermarks could be missed by a wrong selection of locations to sample on the crime scene, resulting in a different probability to recover fingermarks. Other factors that impact on the probability of recovery are the level of background marks that are already present, and the criteria established to determine whether a fingermark is suitable for individualization. For example, if partial fingermarks are present, these will most likely not be recovered if they are not of value for comparison. However, when the question is whether the suspect wore gloves, the presence of these partial fingermarks may very well influence the interpretation at activity level. As a result, the probability to recover fingermarks may vary between the activity level propositions at stake.

2.1.4. Combination of transfer, persistence and recovery

All three variables transfer, persistence and recovery influence the probability of the findings separately, but they cannot be clearly separated. If no fingermark is recovered, it does not automatically mean that the fingermark was not present (transfer). The fingermark could have been degraded such that visualization was not possible (persistence), the chosen enhancement technique could have been unsuccessful (recovery) or it may be the result of a combination of these factors. Therefore, these variables are often taken together and a single probability is assigned to the findings.

2.1.5. Background fingermarks

There are often already fingermarks present on items that are unrelated to the activities at stake. This means that the fingermarks could have already been present on the item before the alleged activity took place or may have ended up on the surface after the alleged activities took place. Fingermarks that are transferred to the surface by actions unrelated to the activities at stake are considered as background fingermarks. Consider, for example, that the issue is whether a suspect stabbed the victim with a knife or that an unknown person stabbed the victim with the knife. Say we find fingermarks of the suspect on the handle, as well as some fingermarks of one or more unknown individuals. Now the weight of the evidence given these two propositions would depend on the relation that the suspect has with the item (e.g. could he have handled the knife prior to or after the incident?), but also on the probability that we find background fingermarks on the handle of this specific knife. If the knife was cleaned recently, that probability may be low and the recovery of fingermarks of an unknown individual may support the suspect's proposition. However, if we have a high expectation of recovering background fingermarks (for instance because the knife is not a personal item and was in common use) the observed fingermarks of unknown individual(s) may be neutral towards the two propositions. The probability that these unknown fingermarks belong to background levels of fingermarks on the item should therefore be taken into consideration. During investigation, it is therefore important to consider the general activities that occurred prior to or after the alleged activities that may have resulted in fingermarks on the item.

2.2. Manner of deposition

2.2.1. Position of the hand and fingers during deposition

The way in which the fingermarks are deposited on a surface depends on the positioning of the hand and fingers during deposition. The position of the hand and fingers on an item may differ between activities, which is determined by the purpose of the activity, the anatomy of the human body and the physical characteristics of the item.

The anatomy of the human body causes restrictions in movements of the limbs. Due to these restrictions, the possible positions of the hand and fingers on an item are limited. The physical characteristics of the item also influence the position of the hand and fingers on an item. These characteristics include size, weight, shape, structure, type of material, its function etc. Consider that someone grasps a knife for stabbing: he or she most likely grabs the knife at the handle due to the shape and structure of the knife. The physical characteristics of the handle of the knife influence the positioning of the hand and fingers, as may the purpose of the activity: cutting a piece of bread versus stabbing may for instance affect the way the knife is held.

Since the movements, the physical characteristics of the item and the goal of the activity may differ between activities, the position of the hand and fingers provides information that may assist in evaluating the findings given activity level propositions. Since it can be difficult to describe the position of the hand and fingers directly, we describe the position of the hand and fingers during deposition through four variables: location of the fingermarks, direction of the fingermarks, part of the hand that left the fingermark, and pressure.

2.2.2. Location of the fingermarks

The position of the hand and fingers on an item during deposition influences the location of the fingermarks on the item. de Ronde, van Aken, de Puit and de Poot [18] designed a model that can be used to analyze the location of fingermarks on 2-dimensional items given different activities. With the use of this model, pillowcases could be separated in the two activity classes smothering and changing, based on the location of the fingermarks on the pillowcases. This shows that the location of fingermarks on an item provides information on the activity that the donor carried out, and is therefore an important variable to take into account.

2.2.3. Direction of a fingermark

When touching a surface, the hand and fingers are positioned in a certain direction. This direction varies between different activities and as such may be distinctive for particular activities. In the balcony case example, the fingermark direction as a result of climbing the balcony may be different from the fingermark direction as a result of leaning on the railing. The variable direction is used by crime scene officers to make inferences during the investigation phase on a crime scene. An example of this is that fingermarks found pointing inwards on the inside of a broken window frame are often considered to be related to the activity of climbing through a window during a burglary. However, there are no studies that report on the direction of fingermarks in relation to activities. The probability to find a certain fingermark direction under the different propositions may provide information on the activity level.

2.2.4. Area of friction ridge skin

Different activities require the use of different parts of the hand and therefore the area of friction ridge skin that left a fingermark may provide information on the activity. Consider the balcony case example: it may be more probable to recover a complete palm impression on the railing if the suspect climbed the balcony, than if

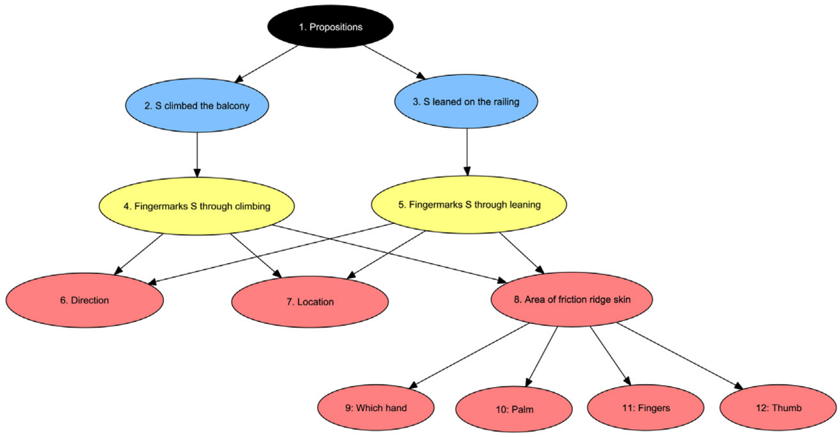

Fig. 1. Bayesian network for the evaluation of fingermarks at activity level in case example 1.

the suspect simply touched the railing while standing on the balcony. The area of friction ridge skin that left the mark can be determined when the donor of the fingermark is known. In cases where a suspect or a corresponding reference print is absent, determining the area that left the print may be difficult.

Although recent research has focused on determining whether it was a left-hand or a right-hand that deposited an individual fingerprint [19–21], assigning a specific finger to a fingermark is still a topic for further research. Nevertheless, forensic examiners are trained to nominate corresponding fingers to fingermarks based on the size, pattern type, shape, etc. This information might be very valuable for the evaluation of fingermarks given activity level propositions. If a likelihood ratio can be determined on whether a recovered fingermark comes from a specific finger, or comes from another area of friction ridge skin, this information can be used in the evaluation of the findings.

2.2.5. Pressure

When friction ridge skin touches a surface, the shape of the skin changes as a result of the pressure applied on the surface and the pliability of the skin. Maceo [22] identifies two types of pressure of a finger on a surface: vertical pressure and horizontal pressure. An increased vertical pressure results in more points of contact with the surface, causing a broader fingermark [23]. Furthermore, vertical pressure affects the width of the ridges and the furrows in a fingermark [24]. As a result, the size of a fingermark and the width of the ridges in a fingermark may provide information about the vertical pressure applied. However, we expect that it will be very difficult to determine the vertical pressure applied to a surface by just looking at the fingermark, since the size of a fingermark, the width of the ridges and the condition of the skin varies greatly between donors.

Pressure in the horizontal plane causes deformation of the skin that may result in a distortion of the fingermarks in the form of smears or swipes [22]. This pressure distortion is often directional, and the distortion seldom moves in two directions [22,24]. Studying these directional distortions in a fingermark can be of greater value for the interpretation at activity level. The probability of detecting a pressure distortion in a particular direction may be different for two activities and this information can be used in the assessment. Another possibility is that some activities may always result in distorted fingermarks. If the probability to obtain a distorted fingermark differs for two activities, this information may be of great value for the activity level interpretation.

3. Bayesian network construction

With the variables identified, we show the implementation of these in a Bayesian network. In this paper, we focus on fingermark grips present on an item. By a grip, we refer to a collection of fingermarks for which it is assumed they are left in one and the same placement of the hand. This means the considered marks can vary from one fingermark to a complete hand mark, although they originate from one and the same hand and be deposited at the same time. In this paper, we assume that the source of the fingermarks is identified or unknown. Recent literature on fingermarks at source level focus on a more probabilistic approach to present the evidential strength of a match [1,25]. The implementation of this probabilistic source level information in Bayesian networks is considered outside the scope of this paper; we refer the reader to Taroni, Biedermann, Bozza, Garbolino and Aitken [4].

We built three different Bayesian networks, each based on a version of the balcony case example described in the introduction of this paper. In the first case example, one grip is recovered on the railing and it is questioned whether the suspect climbed the balcony or leaned on the balcony. The second case example focuses on the question of whether the suspect climbed the balcony or someone else climbed the balcony. In the final case example, the implementation of multiple grips is discussed for the question whether the suspect climbed the balcony or someone else climbed the balcony. All three networks were built using the software Hugin (version 8.6)[2] and can be found in the supplementary material. For the purpose of illustration, we added some fictional probabilities in the network for the first case example. The probabilities used in this example are solely based on informed judgement of the authors, and are not based on any scientific experiments or published data.

Because the purpose of this paper is to show the construction of Bayesian networks for the evaluation of fingermarks at activity level, we do not elaborate on how the variables can be objectively measured, nor do we aim to assign exact probabilities to the network. The main focus will be on the considerations a forensic scientist has to make when creating a Bayesian network to evaluate fingermarks given activity level propositions. In the discussion, we will elaborate on how probabilities can be assigned to the nodes and we propose topics for further research that will give substance to these probability estimations.

[2] https://www.hugin.com.

3.1. Case example 1: Nature of the activity disputed

3.1.1. Background information

Consider the balcony case example we described in the introduction. The police found a grip of fingermarks on the railing of the balcony, which leads to the assumption that the perpetrator entered the apartment via the balcony. The suspect, found through a database search, claims that his fingerprints are not left on the balcony due to an unauthorized intrusion via the balcony, but during a legal visit to the woman when leaning on the railing while smoking a cigarette. The dispute of the defense is aimed at the nature of the activity [26], resulting in the following activity level propositions:

H_p: S climbed the balcony and did not lean on the railing.

H_d: S leaned on the railing and did not climb the balcony.

Following the process described by Taylor, Biedermann, Hicks and Champod [27], we constructed the Bayesian network shown in Fig. 1, using the same colouring scheme. Sections 3.1.2–3.1.7 describe the nodes, the dependencies and the considerations for the states of each node. We constructed this network to evaluate a positive result, e.g. a fingermark found on a surface. If no marks are recovered, the proposed Bayesian network would only consist of nodes [1] to [5], since determining the findings [6] to [12] is impossible.

3.1.2. Node [1] propositions

The black node *Propositions* in Fig. 1 represents the main activity level propositions. This node has two states, H_p and H_d, representing respectively the proposition of the prosecution and the defense. Assignment of the prior probabilities is generally outside the domain of the forensic scientist. For the purpose of this example, we have assigned equal prior probabilities to each proposition (Table 1).

Table 1
Prior probability table for the node [1] Propositions in Fig. 1.

Propositions	Probability
H_p: S climbed the balcony and did not lean on the railing.	0.5
H_d: S leaned on the railing and did not climb the balcony.	0.5

3.1.3. Nodes [2] S climbed the balcony and [3] S leaned on the railing

The propositional node implies two activity nodes: *S climbed the balcony* and *S leaned on the railing*, denoted blue in Fig. 1. We defined the states 'true' and 'false' to both nodes. The probabilities of the states of node *S climbed the balcony* (Table 2) and node *S leaned on the railing* (Table 3) are conditioned on the states of node *propositions.* Table 2 shows that given that H_p is true, the node *S climbed balcony* is true with probability $p = 1$ and false with probability $p = 0$. If H_d is true, the node *S climbed the balcony* is true with probability $p = 0$ and false with probability $p = 1$. For the probability table of node *S leaned on the railing* shown in Table 3, the reverse holds.

Table 2
Conditional probability table for the node [2] S climbed the balcony in Fig. 1.

Propositions	H_p	H_d
S climbed the balcony:		
True	1	0
False	0	1

Table 3
Conditional probability table for the node [3] S leaned on the railing in Fig. 1.

Propositions	H_p	H_d
S leaned on the railing:		
True	0	1
False	1	0

3.1.4. Nodes [4] Fingermarks S through climbing and [5] Fingermarks S through leaning

As a result of the activities climbing or leaning, fingermarks ended up on the railing. In Fig. 1, the mechanisms by which the activities lead to the findings are represented by the yellow nodes *Fingermarks S through climbing* and *Fingermarks S through leaning*, both with states 'true' and 'false'. Within these nodes, the combined probabilities of transfer, persistence and recovery of the fingermarks as a result of the proposed activities are considered.

Table 4 shows the conditional probability table for the node *Fingermarks S through climbing*. This node depends on the activity node *S climbed the balcony*. Given that *S climbed the balcony* is true, P_a denotes the probability to obtain fingermarks given the activity climbing. This incorporates the probabilities for transfer, the persistence and the recovery of fingermarks on the railing through climbing. From the fact that the states of nodes are mutually exclusive and exhaustive follows that the probability that there is no transfer, persistence and recovery of fingermarks through climbing is equal to $1 - P_a$. The probability table for the node *Fingermarks through leaning* is constructed in an equal manner.

Table 4
Conditional probability table for the node [4] Fingermarks S through climbing in Fig. 1.

S climbed the balcony	True	False
Fingermarks through climbing:		
True	P_a	0
False	$1 - P_a$	1

3.1.5. Node [6] direction

One aspect we can observe from the recovered fingermarks is their direction. The node for this variable is shown by the colour red in Fig. 1. Before the direction of the fingermarks can be determined, the transfer, persistence and recovery of the fingermarks had to be successful, which means that the node *Direction* in the network is dependent on the probability to obtain fingermarks under the alleged activities. This is shown in Fig. 1 by drawing an arrow from *Fingermarks through climbing* and *Fingermarks through leaning* to the node *Direction*.

There are multiple options to define the states of the node *Direction*; theoretically, every angle could be a separate state. In our case example, we chose to define two states for the direction of the fingermarks: the fingermarks are pointing inwards (to the house) and the fingermarks are pointing outwards (away from the house). The conditional probability table of the node *Direction* is shown in Table 5. Assume that *fingermarks through climbing* is true and

Table 5
Conditional probability table for the node [6] Direction in Fig. 1.

Fingermarks through climbing	True		False	
Fingermarks through leaning	True	False	True	False
Direction of fingermarks:				
Inwards	*	P_{c_1}	P_{d_1}	*
Outwards	*	$1 - P_{c_1}$	$1 - P_{d_1}$	*

(*) denotes the fact that these probabilities represent situations which will not occur because the activities climbing and leaning are mutually exclusive in our example, and the network is not constructed to evaluate the absence of fingermarks.

fingermarks through leaning is false, the probability to find inward pointing fingermarks is denoted by P_{c_1}.

3.1.6. Node [7] location

Similar to the node *Direction,* the node *Location* is dependent on the nodes *Fingermarks through climbing* and *Fingermarks through leaning*, as shown by the arrows between these nodes and the node *Location* in Fig. 1. In our case example, we assume that there is no direct dependency between the variable *Location* and the variable *Direction*. The probability to find the fingermarks on a particular location on the railing does not directly depend on whether the fingermarks are placed inwards or outwards and vice versa; they both directly depend on the activity that is carried out.

Fig. 2 shows the top view of the balcony. During the investigation, it was determined that the only way to climb the balcony is via the drain pipe located on the left side of the balcony. For the states of the node *Location,* we decided to divide the railing into four areas: the left beam, the middle/left beam (with planter), the middle/right beam and the right beam, as shown in Fig. 3. Again, there are many ways to choose the possible states. For this scenario, we consider dividing the railing into these four areas appropriate given the structure and setup of the balcony. The left side is screened off by the door when open, the planter shields the railing and the four surface areas are approximately equal.

The probability table for the node *Location* is shown in Table 6. Since there are four possible states, we denoted the probabilities of the states left, left/middle, right/middle and right in case *Fingermarks through* climbing is true and *Fingermarks through leaning* is false with $P_{e_1}, P_{e_2}, P_{e_3}$ and $1-(P_{e_1}+P_{e_2}+P_{e_3})$. The probabilities in case *Fingermarks through climbing* is false and *Fingermarks through leaning* is true are denoted with $P_{f_1}, P_{f_2}, P_{f_3}$ and $1-(P_{f_1}+P_{f_2}+P_{f_3})$.

3.1.7. Node [8] area of friction ridge skin with sub-nodes [9] which hand, [10] palm, [11] fingers and [12] thumb

Given that it is known that the suspect left the fingermarks on the railing, the corresponding area of the hand that left the fingermarks can be determined. The node *Area of friction ridge skin* with its sub-nodes *Which hand, Palm, Fingers* and *Thumb* are used to incorporate the variable area of friction ridge skin that left the fingermarks, as discussed in Section 2.2.4.

In our case example, we chose to divide the hand that left the fingermark(s) in three areas: the palm, the fingers and the thumb. Within the nodes *Palm, Fingers* and *Thumb*, the part of the hand that left the marks can be specified. Each node has two possible states: ‘true’ and ‘false’. Whether the marks came from the right or left hand can be specified within the node *Which hand*, also with possible states ‘true’ and ‘false’. All these nodes are connected to the summary node *Area of friction ridge skin,* that combines all the information provided in the previous nodes. In this node, the probability of all possible combinations of the states of the nodes *Which hand, Palm, Fingers* and *Thumb* is summarized.

In some cases, differentiation between each finger or even between specific areas on the hand may be more appropriate since the probability of occurrence of certain areas may differ between the alleged activities. A direct result of defining smaller areas on the hand is that the number of states for the node *Area of friction ridge skin* increases substantially, since each combination of the specified areas for each hand should be assigned a probability. For example, dividing the hand into six regions (five fingers and a palm) and accounting for the possibility that the left or the right hand is used, already results in 126 combinations. Assigning probabilities to all these separate combinations may become a difficult task. Since in our case example, we expected the probabilities to observe fingermarks of a specific finger to differentiate between climbing and leaning, we choose the three states ‘palm’, ‘fingers’ and ‘thumb’. Table 7 shows the probability table for the node *Area of friction ridge skin.* From this table, we can observe that a differentiation of 3 areas of the hand results in 14 possible states to which probabilities have to be assigned, varying from the probability to observe only the left-hand palm, to observing the combination of the right-hands’ fingers, palm and thumb. We did not take into account combinations of the right and the left hand, since we limited our network to one grip of fingermarks for which it is assumed the fingermarks are deposited by one hand.

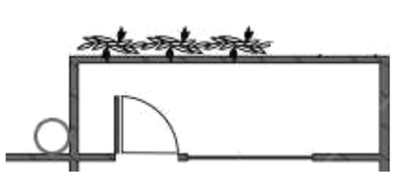

Fig. 2. Top view of the balcony in scenario 1.

Fig. 3. The four different areas representing the states of the node ‘Location’ in Fig. 1.

3.2. Case example 2: Actor that carried out the activity disputed

3.2.1. Background information

Consider the same scenario as described in case example 1, but instead of claiming that the climbing did not take place, the suspect claims that someone else must have climbed the balcony. He states that he visited the apartment a week earlier on invitation by the woman and smoked a cigarette on the balcony while leaning on the railing. The woman confirms the information that S visited a week earlier. The dispute of the defense is now aimed at the actor of the activity [26], resulting in the following activity level propositions (defined as such in node [1] *Propositions* in the Bayesian network shown in Fig. 4):

H_p: *S climbed the balcony and S leaned on the railing.*

H_d: *U climbed the balcony and S leaned on the railing.*

The police still found only one grip of fingermarks. However, this situation is different from case example 1 since if the fingermark grip belongs to S, the probability that there are no fingermarks found of an unknown individual have to be taken into account. This resulted in the Bayesian network shown in Fig. 4.

3.2.2. Nodes [2] U climbed the balcony, [3] S climbed the balcony and [4] S leaned on the railing

The propositions now imply three activities, which are defined with the nodes *U climbed the balcony, S climbed the balcony* and *S leaned on the railing*, each with states ‘true’ and ‘false’. Tables 8–10 show the probability tables for these nodes. For example, in Table 8, given that H_p*: S climbed the balcony and S leaned on the railing* is true, the probability for the state ‘true’ of the node *U climbed the balcony* is 0 and the probability for the state ‘false’ is 1.

3.2.3. Nodes [6] Fingermarks U through climbing, [7] Fingermarks S through climbing and [8] Fingermarks S through leaning

The three different activities each imply a different process by which fingermarks were deposited and persisted on the railing, represented by the nodes *Fingermarks U through climbing, Fingermarks S through climbing* and *Fingermarks S through leaning.* These nodes have the states ‘true’ and ‘false’ and their probability tables

Table 6
Conditional probability table for the node [7] Location in Fig. 1.

Fingermarks through climbing	True		False	
Fingermarks through leaning	True	False	True	False
Location of fingermarks:				
Left	*	P_{e_1}	P_{f_1}	*
Middle/left	*	P_{e_2}	P_{f_2}	*
Middle/right	*	P_{e_3}	P_{f_3}	*
Right	*	$1-(P_{e_1}+P_{e_2}+P_{e_3})$	$1-(P_{f_1}+P_{f_2}+P_{f_3})$	*

(*) denotes the fact that these probabilities represent situations which will not occur because the activities climbing and leaning are mutually exclusive in our example, and the network is not constructed to evaluate the absence of fingermarks.

Table 7
Conditional probability table for the node [8] Area of friction ridge skin in Fig. 1.

Fingermarks through climbing	True		False	
Fingermarks through leaning	True	False	True	False
Area of friction ridge skin:				
Left – Palm	*	P_{g_1}	P_{h_1}	*
Left – Fingers	*	P_{g_2}	P_{h_2}	*
Left – Thumb	*	P_{g_3}	P_{h_3}	*
Left – Palm – Fingers	*	P_{g_4}	P_{h_4}	*
Left – Palm – Thumb	*	P_{g_5}	P_{h_5}	*
Left – Fingers – Thumb	*	P_{g_6}	P_{h_6}	*
Left – Palm – Fingers - Thumb	*	P_{g_7}	P_{h_7}	*
Right – Palm	*	P_{g_8}	P_{h_8}	*
Right – Fingers	*	P_{g_9}	P_{h_9}	*
Right – Thumb	*	$P_{g_{10}}$	$P_{h_{10}}$	*
Right – Palm – Fingers	*	$P_{g_{11}}$	$P_{h_{11}}$	*
Right – Palm – Thumb	*	$P_{g_{12}}$	$P_{h_{12}}$	*
Right – Fingers – Thumb	*	$P_{g_{13}}$	$P_{h_{13}}$	*
Right – Palm – Fingers - Thumb	*	$1-(P_{g_1}+\cdots+P_{g_{13}})$	$1-(P_{h_1}+\cdots+P_{h_{13}})$	*

(*) denotes the fact that these probabilities represent situations which will not occur because the activities climbing and leaning are mutually exclusive in our example, and the network is not constructed to evaluate the absence of fingermarks.

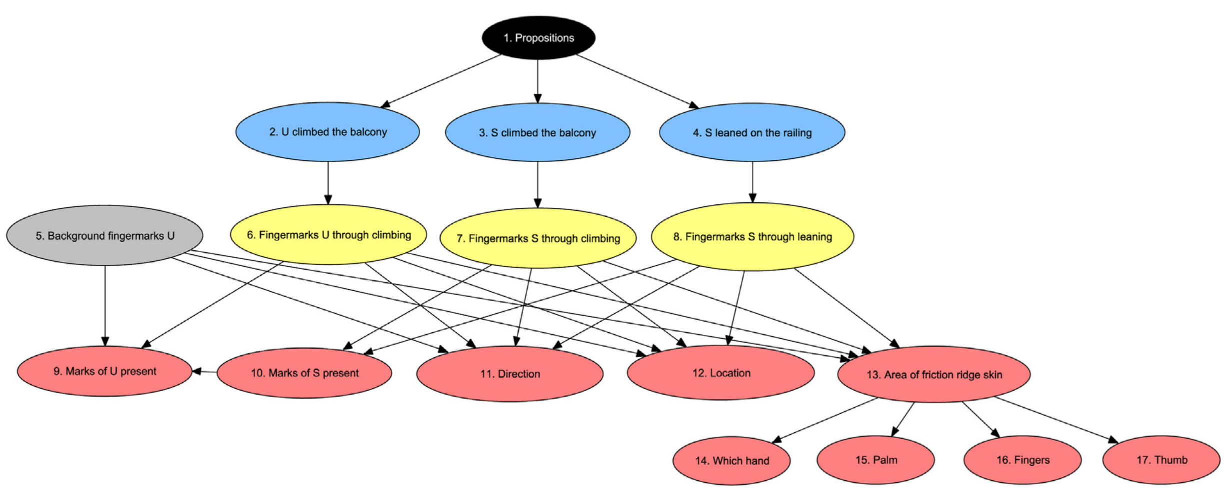

Fig. 4. Bayesian network for the evaluation of fingermarks at activity level in case example 2.

are similar to the probability table for the node *Fingermarks through climbing* in case example 1, shown in Table 4.

3.2.4. Node [5] background fingermarks U

In case example 2, there is another mechanism possible that needs to be considered: fingermarks of one or more unknown persons could already have been present prior to the activities that have taken place. This is denoted by the root node *Background fingermarks U*, denoted by the colour grey in Fig. 4, with states 'true' and 'false'. Within this node, we consider the probability of observing background fingermarks on the railing that are not a result of the disputed activities. In case no unknown fingermarks were found besides the fingermarks of S, the background node will be in state 'false' with a probability $p = 1$.

3.2.5. Nodes [9] marks of U present and [10] marks of S present

This section still focuses on one grip of fingermarks deposited during one hand placement, there are only two options for the

Table 8
Conditional probability table for the node [2] U climbed the railing in Fig. 4.

Propositions	H_p	H_d
U climbed the balcony:		
True	0	1
False	1	0

Table 9
Conditional probability table for the node [3] S climbed the railing in Fig. 4.

Propositions	H_p	H_d
S climbed the balcony:		
True	1	0
False	0	1

Table 10
Conditional probability table for the node [4] S leaned on the railing in Fig. 4.

Propositions	H_p	H_d
S leaned on the railing:		
True	1	1
False	0	0

Table 11
Conditional probability table for the node [10] Marks of S present in Fig. 4.

Fingermarks S through climbing	True		False	
Fingermarks S through leaning	True	False	True	False
Marks of S present:				
True	1	1	1	0
False	0	0	0	1

source of the fingermarks: the fingermarks are from an unknown person U or the fingermarks are from S, denoted by the findings nodes *Marks of U present* and *Marks of S present*. Both nodes have states 'true' and 'false'. The arrow between these nodes represents the dependency between them: if *Marks of S present* is true, *Marks of U present* cannot be true.

The probability tables for the nodes *Marks of S present* and *Marks of U present* are shown in Tables 11 and 12. The node *Marks of S present* depends on the two nodes *Fingermarks S through climbing* and *Fingermarks S through leaning*. Table 11 shows that if one of these nodes is in state 'true', the probability that there are marks of S present is 1. If both of these nodes are in state 'false', there is a probability of 0 that there are marks of S present. The node *Marks of U present* depends on three nodes: *Fingermarks U through climbing, Background fingermarks U* and *Marks of S present*. Table 12 shows that if the node *Marks of S present* is true, the probability that there are marks of U present is false. This is because we focus on one grip of fingermarks left during one placement.

3.2.6. Finding nodes [11] to [17]

The nodes *Direction,Location,* and *Area of friction ridge skin* are defined the same way as described in previous Sections 3.1.5–3.1.7, with an additional arrow from the nodes *Background fingermarks U* and *Fingermarks U through climbing.* The nodes *Which hand, Palm, Fingers* and *Thumb* are defined exactly the same way as described in Section 3.1.7. An example of the probability table for the node *Direction* in Fig. 4 is shown in Table 13.

3.3. Case example 3: Multiple grips

3.3.1. Background information

Often there is more than one grip of fingermarks found on an item. Suppose that in addition to the first grip, another grip is found on the railing. Again, the suspect claims that he visited the apartment a week earlier and leaned on the railing of the balcony and this information is again confirmed by the woman. The propositions brought forward by the prosecution and the defense are the same as used for case example 2:

H_p: *S climbed the balcony and S leaned on the railing.*

H_d: *U climbed the balcony and S leaned on the railing.*

Now the Bayesian network should account for two grips, resulting in the Bayesian network shown in Fig. 5.

3.3.2. Structure of the network

The Bayesian network in Fig. 5 consists of four 'modules'. The network starts with a proposition node *Propositions* [1], followed by the nodes describing the alleged activities: *U climbed the balcony,* [3] *S climbed the balcony* and [4] *S leaned on the railing.*

Table 12
Conditional probability table for the node [9] Marks of U present in Fig. 4.

Fingermark U through climbing	True				False			
Background fingermarks U	True		False		True		False	
Marks of S present	True	False	True	False	True	False	True	False
Marks of U present								
True	*	*	*	1	*	1	0	0
False	*	*	*	0	*	0	1	1

(*) denotes the fact that these probabilities represent situations which will not occur because the activities climbing and leaning are mutually exclusive in our example, and the network is not constructed to evaluate the absence of fingermarks.

Table 13
Conditional probability table for the node [11] Direction in Fig. 4.

Background fingermarks U	True								False							
FM U through climbing	True				False				True				False			
FM S through climbing	True		False		True		False		True		False		True		False	
FM S through leaning	True	False	True	False	True	False	True	False	True	False	True	False	True	False	True	False
Direction:																
Inwards	*	*	*	*	*	*	*	P_{i_1}	*	*	*	P_{j_1}	*	P_{k_1}	P_{l_2}	*
Outwards	*	*	*	*	*	*	*	$1-P_{i_1}$	*	*	*	$1-P_{j_1}$	*	$1-P_{k_1}$	$1-P_{l_2}$	*

(*) denotes the fact that these probabilities represent situations which will not occur because the activities climbing and leaning are mutually exclusive in our example, and the network is not constructed to evaluate the absence of fingermarks.

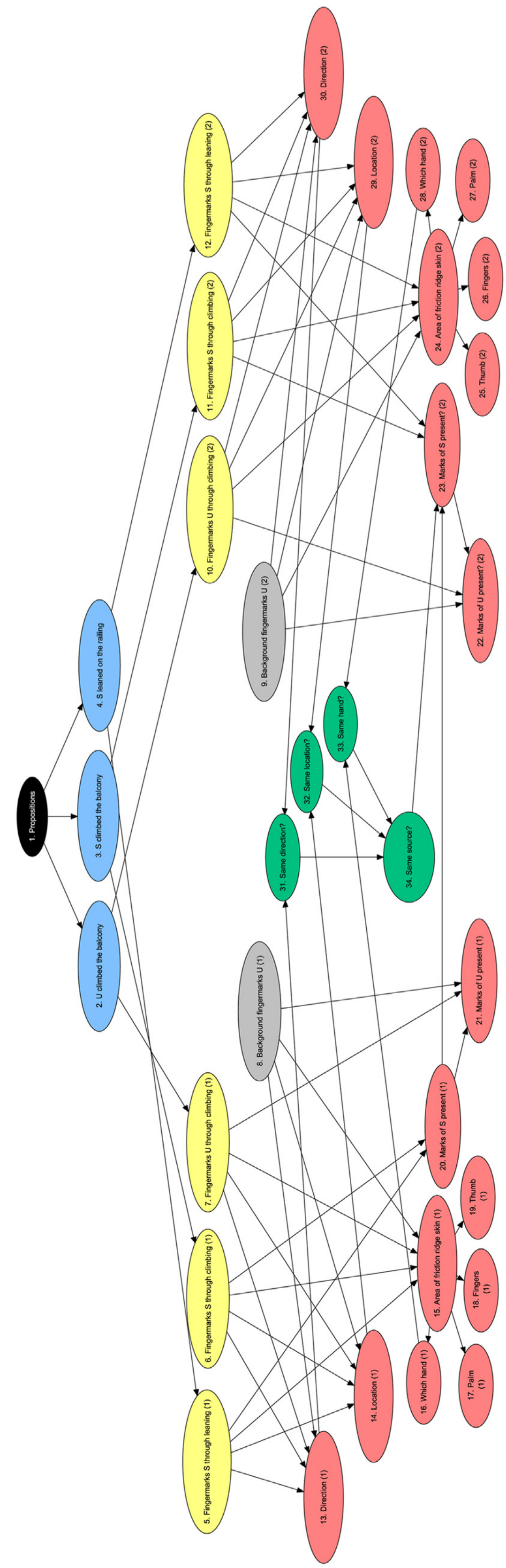

Fig. 5. Bayesian network for the evaluation of two grips of fingermarks at activity level in case example 3.

These nodes have the same setup as in case example 2. Below these nodes are two nearly identical modules that represent two distinct fingermark grips. The first grip of fingermarks is described by the nodes on the left-hand side of the network, indicated by (1). The second grip of fingermarks is described by the nodes indicated by (2). Between these two sub-networks is a module consisting of four green nodes that describe dependencies between the two traces. We consider conditional dependencies between the two traces based on the location of the marks, the direction of the marks and whether or not the two marks were left by the same hand since the findings may be dependent on these factors. We consider them conditionally independent from the propositions. We chose these dependencies since we consider that the probability of the two marks being from the same donor is higher when they are found at the same location, have the same direction and are left by two different hands, than if either location or direction differ (where locations within reach of both arms still have an increased probability for the fingermarks being from the same source).

If the two grips are deposited during the same activity (holding the railing with both hands while climbing or leaning on the rail with both hands), there are two optional situations: the deposition of the two marks is strictly constrained in time, e.g. they must have been placed at the exact same moment during the same activity or the deposition of the two marks is less constrained in time and multiple interactions between hands and the railing took place during the same activity. To both situations, it applies that if the two fingermark grips are found in close proximity, this will influence the probability that they were left by the same individual, regardless of the activities defined in the propositions that led to their deposition.

If we assume the two marks are strictly constrained in time and were left through the same activity, given the case circumstances, there is a high probability that they will have the same direction, since it is unlikely to place one hand inwards and one hand outwards when carrying out the same activity in the same moment in time. Furthermore, if the two marks were left through the same activity at the same time, they cannot have been left by the same hand.

However, since both the activities leaning and climbing are a dynamic process, it is unlikely that this assumption holds. If multiple interactions between hands and railing may have taken place, it is not unlikely to find multiple marks of the same hand close together. Also, depending on how strict or broad the activities are defined in dynamics and time, it may be considered equally probable to find the marks having the same direction or a different direction. With a very broad definition and multiple interactions with the railing over extended periods of time, only location is expected to be a dependent factor between the two marks.

We have added four nodes to the network that model these dependencies. Node [31] *Same direction?* models whether both marks have the same direction or not (respectively state 'true' or 'false'), and is dependent of the direction nodes for the two separate grips. If the direction of both grips is equal, the node *Same direction?* is in state true with a probability $p = 1$. Otherwise, the node *Same direction?* is in state false with a probability $p = 1$. Node [32] *Same location?* models whether both marks have the same location. The states of this node consist of all possible combinations of the states for the nodes *Location (1)* and *Location (2)*, which results in ten combinations. If *Location (1)* is left and *Location (2)* is left, the node *Same location?* is in state 'left-left' with a probability of $p = 1$ Choosing for two possible states 'true' and 'false' is also a possibility. However, in this case the proximity of two consecutive beams cannot be taken into account in the node [34] *Same source*. The dependency between two hands is modelled within the Node [33] *Same hand?*, with states 'true' and 'false'. If *Which hand (1)* and *Which hand (2)* are both left, the node *Same hand?* is true with a probability of p=1The node [34] *Same source?* contains a probability table that holds the probabilities for the fingermarks being from the same donor based on their respective locations, direction and left or right hand setting. Additionally, node [23] *Marks of S present (2)* is now dependent on the node [34] *Same source* and node [20] *Marks of S present (1)* (in addition to nodes [11] and [12]).

This network could be extended to a network that allows for the evaluation of more than two grips of fingermarks, by concatenating multiple sub-networks in the same way. When constructing such a network, possible new dependencies between variables describing different grips should be considered. A combined network accounting for multiple grips makes a complete analysis of all the fingermarks present on an item possible.

4. Discussion and conclusion

In this paper, we have described a framework for the evaluation of fingermarks given activity level propositions with the use of Bayesian networks. We provided an overview of the current state of knowledge of the variables that provide information on fingermarks given activity level propositions, followed by an implementation of these variables in a Bayesian network using three case examples. The resulting networks enables the evaluation of (multiple) fingermark grips present on an item given propositions that dispute the activity that was carried out or given propositions that dispute the actor that carried out the activity.

The Bayesian networks proposed in this paper could function as basic networks for the evaluation of fingermarks, with the possibility to be modified according to specific case circumstances. Furthermore, parts of the network may function as building blocks to create new networks for items other than a balcony railing, to evaluate fingermark grips given activity level propositions. Another advantage of using of Bayesian networks is that it makes the process of evaluation of the findings explicit. The network can be used as a tool to discuss the selected variables, the dependencies between them and the probabilities used, resulting in open discussions in court.

The principles discussed in this paper are meant to be used as a guideline to help forensic scientists make well-considered choices depending on the case at hand. The proposed list of variables is a recommendation: it depends on the case circumstances which variables may be important to consider. The choice of the states of the variables also depends on the case circumstances, the possibilities to objectively measure the possible states and the feasibility of assigning probabilities to the states. These factors need to be carefully considered when selecting the states of the nodes. Similarly, we proposed dependencies between the variables based on our case example, which should be reconsidered when applying the framework to a different case example.

The final step to complete a Bayesian network is to assign probabilities to the nodes [28]. According to Taylor, Kokshoorn and Biedermann [29], a forensic scientist has a number of options to do this (mentioned in order of preference): perform experiments by simulating the case circumstances, use values reported in literature from studies using similar case circumstances and outline the differences when reporting, consider a range of reasonable values and examine the sensitivity of the LR (see [30]), assign values based on the expert's experience or knowledge, or not carry out an evaluation. For fingermarks, the current situation is that evaluations of fingermarks given activity level are not carried out by forensic experts. This leaves the evaluation of fingermarks given activity level propositions up to the court although the forensic scientist has the specialized knowledge regarding the variables that is required to properly assign probabilities [29].

In the field of forensic biology, an increasing body of literature is available that aids in understanding the factors influencing transfer, persistence and recovery of DNA in relation to activities (see for example [31,32]). These studies involve experiments in which participants carried out activities that resulted in touching surfaces or items, and factors like transfer and persistence were evaluated in relation to the activities performed. The study of fingermarks in time and space would benefit from similar experimental designs. Experiments into probabilities of transfer, persistence, recovery, direction, location of fingermarks, or what fingers are used when carrying out different activities with a particular item would help forensic scientists to assign probabilities to these variables in cases with similar case circumstances. Although the obtained probabilities may not always be directly applicable to other cases, the experimental data may still contribute to a scientific knowledge base [29] and may contribute to a better understanding of the general mechanisms of fingermark dynamics.

Other recommendations for further research are designing methods to objectively measure a specific variable. For example, there is no method available to objectively measure the direction of a fingermark on a surface. Another example is the variable transfer: how do we measure the transfer of a fingermark to a surface as a result of an activity? Nowadays, fingermarks can be scored (for example by the CAST scale [14]) to compare the quality for individualization purposes. However, the quantity of fingermarks transferred to a surface may also provide information on activity level. These examples show that for some variables describing fingermarks at activity level, a clear definition or method to measure the variable is required before the variables can be described by case specific experiments.

With this paper, we want to initiate a discussion about the evaluation of fingermarks given activity level propositions. Until now, this topic has barely been touched upon, possibly because the necessity is not acknowledged. However, an evaluation of fingermarks given source level propositions does not always amount to the activity [9]. In these cases, an evaluation of the fingermarks given activity level propositions could affect the strength of the evidence within the case circumstances. We hope this paper will lead to new perspectives on this topic and stimulates opportunities for further research.

Author's contribution

Anouk de Ronde: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – Original draft, Writing – Review and Editing, Visualization, Project administration. Bas Kokshoorn: Conceptualization, Methodology, Software, Formal analysis, Writing – Review and Editing, Visualization. Christianne de Poot: Conceptualization, Methodology, Writing – Review and Editing, Supervision, Funding Acquisition. Marcel de Puit: Conceptualization, Methodology, Writing – Review and Editing, Supervision, Funding Acquisition.

Conflicts of interest

None declared.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.forsciint.2019.109904.

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