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The foot in forensic human identification - a review

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Dear Editorial Board of The Foot,

On behalf of myself and my colleagues, I hereby submit the revised manuscript titled "The Foot in Forensic Human Identification – A Review" by Catriona Davies *et al.* for consideration for publication as a review article in The Foot. All co-authors were fully involved in the study and preparation of this manuscript. The contents of this paper have not been presented or published anywhere previously. The manuscript has been revised in accordance with the request of the editor.

We present a review of the literature pertaining to forensic human identification from the foot when recovered in isolation and in particular consider the approaches and methods available for the establishment of a biological profile from limited remains.

We believe that the information presented in this article will be of interest to the readers of The Foot as this has the potential to aid forensic anthropologists and podiatrists in their examination of isolated pedal remains and highlights the deficiencies in the current literature.

Yours Sincerely,

Dr Catriona M Davies PhD.

On behalf of:

Dr Lucina Hackman PhD.

Prof. Sue Black PhD.

CONFLICT OF INTEREST STATEMENT

No conflict of interest is known to the authors

*Title Page (with author identifiers)

The foot in forensic human identification – A review

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Response to Reviewer

In response to the reviewer, the abstract for this article has been added to the manuscript as requested.

SUMMARY

The identification of human remains is a process which can be attempted irrespective of the stage of decomposition in which the remains are found or the anatomical regions recovered. In recent years, the discovery of fragmented human remains has garnered significant attention from the national and international media, particularly the recovery of multiple lower limbs and feet from coastlines in North America. While cases such as these stimulate public curiosity, they present unique challenges to forensic practitioners in relation to the identification of the individual from whom the body part originated. There is a paucity of literature pertaining to the foot in forensic human identification and in particular, in relation to the assessment of the parameters represented by the biological profile. This article presents a review of the literature relating to the role of the foot in forensic human identification and highlights the areas in which greater research is required.

INTRODUCTION

It is incumbent upon forensic practitioners to attempt the identification of any recovered human remains, irrespective of the quantity or the stage of decomposition in which they are found. The process of human identification requires the completion of multiple stages of investigation and the combination of various evidentiary threads which may lead to a putative identity of the deceased. Only once a presumptive identification has been made, can confirmation of identity be sought through the use of DNA or any other primary source of identity. The methods and approaches utilised in this process are, however, dependent on numerous factors including the context in which the remains are found, the anatomical regions recovered and the degree of decomposition or fragmentation of the remains.

In the early stages of the identification process, it is necessary to establish data relating to the four parameters of biological identity, ancestral origin, biological sex, chronological age and living stature (1). From this information, termed a biological profile, the pool of potential identities from documented missing persons may be reduced. While the biological profile may be relatively easy to deduce from remains recovered in a relatively intact state, the absence of certain skeletal elements, particularly the skull, pelvis and long bones increases the complexity of this process.

The discovery of human remains, in various states of decomposition, is a relatively regular occurrence; however there appears to be a bias in the anatomical areas recovered, as the lower limb, and in particular the foot, tends to be discovered in isolation, with at least 9 incidents recorded in the United Kingdom (UK) since 2003 (2-5). This is not particular to the UK and the recovery of isolated pedal remains was brought to the attention of the media by a spate of incidents in the Straights of Georgia, located on the border between Canada and the United States of America, where 14 feet were recovered between 2007 and 2012 (6, 7). More recently, two incidents occurred in New Jersey and San Francisco in a four-week period of 2013 (8, 9). The expanse of territories over which these incidents have occurred highlights the prevalence of cases such as these. It should be noted however that the majority of incidents in which a foot has been recovered in isolation, have been found contained within items of footwear and have been associated with either marine or fluvial biomes (2-7, 10). The presence of the foot within a shoe contains the pedal elements, thus preventing disassociation of the individual bones. In addition, the type of shoe in which the foot is encased may alter the buoyancy characteristics of the foot, and thereby affect the likelihood that the foot will become stranded on the tide line. Within terrestrial biomes, the protective nature of footwear may prevent dissociation of the individual tarsal elements, prevent some aspects of taphonomic alteration, such as animal scavenging and add a degree of protection to the remains, thus preserving the integrity of the pedal skeleton (11-13).

The dissociation of the foot from the remainder of the body may occur through a variety of scenarios, including the normal sequence of post-mortem disarticulation which occurs in terrestrial or aqueous environments; scavenging behaviours of carnivorous fauna; and traumatic amputation, such as may occur during aviation or road traffic accidents or as a result of collision with a ship's propeller (14). Although the mechanisms by which feet may become dissociated from the remainder of the lower limb may be diverse, a factor common to almost all recorded incidents of isolated recovery of a foot in the UK since 2003 is the presence of the foot within an article of footwear, for example training shoes or work boots (2, 4-7, 10). In addition, the robust nature of the tarsal bones makes them more likely to survive inhumation and other taphonomic influences than other, more fragile, elements of the skeleton (13, 15, 16).

Despite the apparent frequency of the discovery of isolated feet, there is a paucity of literature relating to the role of the foot and ankle in forensic human identification. The disarticulation of human remains presents certain challenges relating to establishing the identity of an individual including a reduction in the quantity of information pertaining to identification that can be deduced (17). It is therefore imperative that the method chosen is appropriate to the context and the anatomical region under examination (18). This short communication will present a review of the current trends in the examination of the foot in the context of forensic human identification.

CHOICE OF METHODS

The methods used in the examination of the foot for the purposes of identification will vary depending on whether presumptive identification of the remains has already taken place, such as may have occurred during a closed mass disaster incident where the identities of the individuals involved is known. In such circumstances, the comparison of ante-mortem and post-mortem radiographs of the foot has been used in attempt to support the suspected identification (14). This approach to identification however is contingent upon the presence of recent ante-mortem records relating to the foot and ankle; a source of information which may not be present for every individual. In addition, the comparison of ante-mortem podiatric records with lesions or pathological changes noted in recovered feet may be used to support an identification (19). In the case of a mass disaster where fragmentation of remains has occurred, it may also be possible to re-associate isolated feet with their corresponding limb through anatomical matching with a leg or body with a pedal amputation (20). This approach was used during the triage phase of the identification process that followed the attacks on the World Trade Centre in 2001 and resulted in a reduction in the number of DNA tests required as without anatomical matching of fragmented remains, protocol would have dictated that each fragment be subject to DNA testing (20).

DNA

In the absence of a presumptive identification it may be necessary to establish a biological profile, which, when compared with ante-mortem information may narrow the pool of potential identifications, making the use of alternative primary identifiers such as DNA testing feasible. The current recommendations pertaining to DNA analysis include obtaining a mid-shaft femoral bone sample; however this site is secondary in preference to an intact, multi-root tooth (21). There is however some evidence that certain tarsal elements, in particular the talus, calcaneus and cuneiforms may provide a higher yield of genetic material than may be extracted from other skeletal elements, including the long bones of the upper and lower limbs (21, 22). As a result of this research, the bones of the foot should be considered as a source of genetic material for the purposes of DNA analysis of unidentified remains and may facilitate the reconciliation of disassociated anatomical regions. The ability to recover useable DNA is however dependent on a number of factors including the bone structure, the post-mortem interval, the biome(s) in which the remains have existed since death (i.e. marine, fluvial or terrestrial) and other taphonomic influences (22).

Although the successful use of DNA analysis in human identification is largely restricted to cases where a putative identity is suspected, it may be a useful tool in the re-association of remains recovered in different temporal and spatial locations. This approach has been utilised in both North America and Europe in cases where individual feet, which became disassociated through natural post-mortem disarticulation, were recovered in similar footwear and were subsequently re-united through DNA matching (23, 24). The use of DNA matching in the re-association of human remains has been of particular use in scenarios where substantial fragmentation and commingling of remains has occurred (25). The importance of DNA analysis from the foot and ankle is also highlighted by the use of Improvised Explosive Devices (IEDs) in modern theatres of warfare. As a result of the technologies involved in the manufacture of tactical footwear, the potential recovery of an intact foot may be greater than that of other anatomical areas in the aftermath of an explosive incident (26).

The recovery of isolated feet, particularly in fluvial or marine biomes, may require the origin of the foot to be established as the remains be transported a considerable distance from the point at which they entered the specific environment (27). Although estimation of the point of origin of remains may be possible to some extent in riverine systems, the effect of ocean currents on the path of disarticulated remains is less predictable. It may therefore be necessary to use alternative methods, such as stable isotope analysis, to determine those geographical areas in which the decedent resided prior to their death. The protective nature of footwear in such circumstances renders stable isotope analysis of keratinised tissue from the toenails a viable option (28). As a result of the relationship between diet, geographical location and the isotopic composition of certain tissue types, e.g. keratin; the analysis of specific isotopes including hydrogen, oxygen, carbon and nitrogen within the toenail may provide information relating to the point of origin of the decedent (29). Although this may not lead directly to the identification of the individual to whom the remains belong, the identification of a potential location with which the individual was recently associated may provide information that is vital to the investigation.

Although the use of techniques such as DNA and stable isotope analysis may enable the re-association of fragmented remains or provide information relating to the geographical history of the individual, without a presumptive identity, the successful identification of remains is unlikely. It is therefore necessary to establish information relating to the biological characteristics that may facilitate a reduction in the pool of potential identities.

Biological Identity

Analysis of the bones of the foot in relation to aspects of the biological identity has been conducted for many years, with particular reference being paid to the assessment of biological sex and living stature (12, 15, 17, 30-40). Although some consideration has been given to skeletal age assessment from the juvenile foot and ankle, literature pertaining to this topic is much more limited (41-45). This is also true for the determination of ancestral origin (46, 47).

Sex determination from the foot

It is widely considered that the most sexually dimorphic regions of the adult skeleton are the skull and the pelvic complex, the analysis of which, when considered together, may result in approximately a 90-98% correct classification of biological sex (48). This, however, is dependent on the degree of dimorphism present within the population (12, 49). In the absence of these anatomical regions however, it is necessary to consider alternative approaches to the determination of biological sex.

The examination of the foot in the context of establishing the biological sex of the individual has received some attention from multiple research groups (17, 34, 40).

Within this research there is variation both in the methodological approach taken and the feature(s) of the foot examined. Consequently, not all methods may be applicable to all scenarios. Although a significant body of work has been published relating to the determination of biological sex from the foot, many of these studies are based on the overall morphology and size of the feet of living individuals (17, 34, 39, 40, 50). A number of problems exist pertaining to this method when viewed in the context of its applicability to forensic scenarios as the use of living individuals ensures that the measurements taken are reflective, not of the underlying skeletal structure, but the soft tissue which surrounds it. Consequently, the standards developed from such analyses may only be applicable to cases in which the soft tissue of the foot is preserved in its entirety. In addition, it appears to be relatively common practice for data relating to the size of the foot to be collected in a weight-bearing stance (17, 50). As a result of the forces acting on the foot from body weight and gravity, the size and shape of the foot is altered during weight-bearing compared to that of the unloaded foot. The data derived from analyses conducted in this manner are therefore only applicable to cases in which full body weight (i.e. mass+ gravity) is applied to the foot during forensic examination. It is clear that values generated through these approaches are unlikely to be applicable in the assessment of sex from the disarticulated foot of a deceased individual and it is therefore necessary to consider the potential utility of individual skeletal elements in the determination of biological sex.

Among the tarsal skeleton, the greatest degree of sexual dimorphism has been found in the talus and calcaneus (12, 13, 34, 51). Gualdi-Russo (34) found that calcanei and tali from male individuals exhibited greater osteometric measurements than female individuals in all measurement parameters examined. Through the application of discriminant function analyses, this study observed that when tested on a similar population, cross-validation resulted in between a 94.5% and 97.4% correct classification for males and females respectively according to talar measurements. In contrast, examination of the discriminant functions relating to the calcaneus, cross validation resulted in 89.8% and 88.4% correct classification of females and males respectively. When compared with data obtained from the analysis of an alternative population sample however, the percentage of male individuals for whom biological sex was correctly assigned based on examination of these skeletal elements decreased to

48.2% and 31.9% in the talus and calcaneus respectively. This reduction in the percentage correct classification was not observed in female individuals. The variation in the percentage classification of biological sex according to measurement of the calcaneus and talus observed between male individuals of different population groups may suggest that the relationship between size of these bones and biological sex is affected by additional factors. The results obtained by Gualdi-Russo (34) are supported by those of Harris and Case (12), who observed that measurement of the talus (length and height) yielded the strongest individual measures by which the sex of the individual could be distinguished. It was noted however that the measurements pertaining to each individual tarsal bone yielded correct classification of biological sex in at least 80% of individuals (12).

The findings of the research pertaining to sex determination from the tarsal skeleton suggest that although sexual dimorphism is present within population groups, there is significant overlap in the size and morphology of adult tarsal bones between individuals of either sex from multiple populations. Consequently, it is imperative that this method should only be used where appropriate standards have been developed using a modern sample population specific to the group on which it is to be applied. It must be concluded therefore that although steps have been taken in the determination of sex from the bones of the foot, further research is required in this field.

In addition to the morphological and metric methods of sex determination discussed, the sex of an individual can be identified from analysis of the homologous gene amelogenin, present on chromosome 23 of the human karyotype (52-56). As previously discussed however, the environment to which the foot has been exposed may alter the viability of this approach (57). The application of this time consuming and expensive process must therefore be assessed on a case-by-case basis.

<u>Age estimation from the foot</u>

The process of skeletal age estimation is dependent on the strength of the relationship between chronological age and the stage of development or deterioration of specific skeletal elements or regions (58). The precision with which an estimation of age can be made is therefore dependent on the degree of age related change observed. The developing skeleton therefore presents a greater quantity of information on which to base an estimation of age and therefore may be more accurate and precise than those conducted on individuals who have attained skeletal maturity. To date, no methods have been published for estimating age from the foot in adult individuals. Skeletal age estimation from the bones of the foot is largely restricted to the examination of remains from sub-adult individuals in whom skeletal development is yet to be completed. Despite the relative frequency with which isolated remains of the foot and ankle are recovered, there is a distinct paucity of literature relating to the estimation of age from this anatomical region.

Fetal and neonatal individuals

Although finding isolated juvenile feet is very rare, there may be a requirement to establish the age of fetal or neonatal individuals as part of the DVI process. The techniques used in the estimation of age from fetal remains are dependent on the condition of the remains (i.e. fleshed or skeletal). As with other regions of the developing skeleton, radiographic examination of the foot and ankle may yield information relating to the ossification of the pedal skeleton and therefore the gestational age of the individual. In cases where complete skeletonisation of the remains has occurred, the estimation of age in fetal and neonatal individuals is often determined through the calculation of the maximum length of long bones, including the metatarsals, and the subsequent correlation between this measurement, crown-rump length (CRL) and gestational age (1). Several methods have been produced which facilitate an estimation of age from the fetal foot (59, 60).

Although it is possible to estimate age through the correlation between total length (base of the metatarsal to the articular surface of the head of the metatarsal) or diaphyseal length (base of the metatarsal to the metaphyseal surface) of the metatarsals and gestational age or CRL, a study by de Vasconcellos and Ferreira (59) suggested that the relationship between total length and gestational age was stronger than the reciprocal relationships (i.e. total length v CRL; diaphyseal length v gestational length; or diaphyseal length v CRL). It should be considered however that in a forensic context, diaphyseal length may be a more appropriate measurement due to the absence of secondary centres of ossification. The study of de Vasconcellos and Ferreira (59) also found that with the exception of the fifth metatarsal, the regression of diaphyseal length against gestational age yielded R^2 values greater than 0.8. This indicates that diaphyseal length may be a viable approach to age estimation in fetal remains. The approach used in this method is however dependent on the presence of the metatarsal epiphyses which, depending on the taphonomic influences to which the remains have been exposed, may not be present or recovered. This methodological approach is therefore limited to cases where the metatarsal, though devoid of soft tissue, is found to have retained its epiphysis.

The use of the maximum lengths of the metatarsal bones in skeletal age estimation of fetal individuals has also been applied by Fazekas and Kosa (60) who provided data relating to the mean, maximum and minimum length the metatarsals observed in autopsy specimens. Although believed to be applicable in forensic settings, the data obtained in this study has not been revised since its original publication and may not therefore be applicable to all populations. In addition, the development of the standards produced by Fazekas and Kosa included the estimation of age from crown-heel length from autopsied fetal remains (61). As such, the viability of this approach to age estimation is contingent on the accuracy of the original estimations of age against which metatarsal length was compared and may therefore be liable to error from the inaccurate assessment of CRL (1, 62). It is also necessary to consider the sample population on which the standards of Fazekas and Kosa (60) were developed. As these data were obtained from the analysis of autopsied fetal remains, it is possible that the skeletal growth rate of some individuals included in this sample was not representative of the normal development of a healthy foetus. Consequently, the standards derived from the analysis of this population may include a degree of error related to abnormal skeletal growth or fetal development (58).

Infants, children and adolescents

In the case of the analysis of the skeletonised remains of post-natal juvenile individuals, the numbers of centres of ossification present, in addition to the overall size and morphology of the bones of the foot, may present information pertaining to the age of the individual. Several texts present the summarised timings of appearance and fusion of the bones of the foot (61, 63, 64).

Only two radiographic approaches to skeletal age estimation from the foot and ankle in the post-natal period have been produced in the past fifty years, of which only the Radiographic Atlas of Skeletal Development of the Foot and Ankle (41) has been shown to be of sufficient accuracy to be applicable to skeletal age estimation in the forensic context (41-44). This radiographic atlas, although originally intended as a means of monitoring the skeletal development of children in a clinical setting, may be applied as a standard of radiographic skeletal age assessment in both male and female juvenile individuals until the ages of 15.2 years and 18.2 years in females and males respectively (42).

In addition to the holistic examination of the bones of the foot and ankle in relation to skeletal age estimation in juvenile individuals, it is necessary to consider the potential information that may be gained from the examination of specific elements of the pedal skeleton, for example the proximal epiphysis of the fifth metatarsal or the fusion of the calcaneal epiphysis (45, 65). Although these bones should not be considered independently if other skeletal elements are present, the values presented in these standards suggest that if recovered individually, these skeletal elements may provide some information relating to skeletal age.

Stature estimation from the foot

The calculation of living stature is an established concept in human identification and may be achieved through a variety of methods including the use of linear regression analyses based on long bone lengths, also termed the “mathematical method” and the “anatomical method”, which requires the calculation of the total skeletal height plus the addition of a soft tissue correction factor (66-68). These approaches however are limited to occasions when intact long bones or full skeletons are recovered (68). Due to the relative robusticity of the tarsal skeleton, it is likely that these elements may survive inhumation and their applicability in stature estimation should therefore be considered (32).

The calculation of living stature has been attempted through the use of linear and multiple regression analyses based on various measurements of the calcaneus, talus and metatarsals (16, 30, 32, 51, 68-71). Although many of these studies report the presence of statistically significant relationships between metatarsal length and stature, the strengths of these interactions, as described by the values obtained as the relative co-efficient of determination (R^2) suggest that the relationship between metatarsal length and stature is of insufficient strength for this approach to be utilised in a forensic context (32, 68). While the majority of studies concerning the use of metatarsals in stature estimation include the examination of dry bone, a recent study by Rodríguez *et al*. (72) attempted to determine stature through measuring the length of the metatarsals in radiographic images, the results of which were then compared with the living stature of the individual from whom the radiographs were obtained. The results of these analyses further illustrated the positive correlation between metatarsal length and overall stature, however this study also suggested that the relationship between these factors was too weak to be of forensic relevance (72). Despite the poor R^2 values observed in this study (R^2 =0.534-0.613 for the first metatarsal and R^2=0.498-0.505 in the second metatarsal), the results of this study were consistent with those obtained by Cordeiro *et al.* (32). This may indicate that measurements of the metatarsals for the purpose of stature estimation may be obtained from either radiographic images or post-mortem specimens without significant alteration to the accuracy of the technique. This may of particular importance during disaster victim identification (DVI) incidents as the examination of the physical remains may not always be possible and the use of medical imaging may be required during the anthropological examination (73).

As is the case in many aspects of the biological identification of human remains, inter-population variation in certain osteometric values has been found (68, 72). Consequently, it is necessary for population specific standards to be developed and applied where appropriate. To further assess the validity of stature estimation from the bones of the foot, further research using samples including individuals for whom living stature is known, is required.

Ancestry determination from the foot

While this assessment of ancestry is relatively straight forward if there are certain skeletal regions present, for example the skull, assessment of ancestry from the bones of the foot has not received the same degree of attention in the literature (47). Several studies have however attempted to determine population affinity from morphological features of the calcaneus, including the number of articular facets for the talus (46, 47, 74). It has been suggested that individuals of Caucasoid ancestry are more likely to exhibit three articular facets on the calcaneus (Type A); while individuals of Negroid ancestry are more likely to exhibit two articular facets on the calcaneus (Type B) (47). There is however conflation between individuals of different ancestry and those of different population groups, for example, similarities have been observed in the number of articular facets for the talus in Indian and Nigerian groups, thereby reducing the potential use of this approach (47, 74).

In addition to the morphological approach to ancestry determination from the calcaneus, some authors have attempted to establish parameters for the separation of ancestral groups based on variations in a set of measurements including calcaneal length and breadth (47). Through the application of discriminant function analyses, it has been determined that although variation does exist in metric measurements of the calcaneus, the percentage correct classification is insufficient to establish ancestral origin with accuracy (47).

CONCLUSION

Through anecdotal reports of feet and lower limbs being recovered in isolation, it is clear that there is a requirement for appropriate standards of analysis to be developed for the purpose of forensic human identification. Although the foot and ankle has been examined in respect of some aspects of human identification, there is a general paucity of methods relating to the determination of a biological profile that may be considered applicable to forensic casework. The examination of the foot in living individuals in relation to the estimation of stature and biological sex, though informative, is of limited value in the assessment of the characteristics of a biological profile from skeletal or decomposed remains, particularly in relation to those methods derived from measurements taken in a weight-bearing stance. As the application of force, in the context of weight bearing, affects the size and shape of the foot, the accuracy of methods derived from this approach are influenced by the weight of the individual and the degree of soft tissue present in the foot. In contrast, the radiographic examination of the foot in living individuals may provide reliable, repeatable and accurate information relating to the chronological age of the individual. As an examination of the skeletal maturity, this approach is applicable to the estimation of age individuals in whom skeletonisation is complete or decomposition is advanced.

While some approaches and standards related to certain aspects of the biological profile (age) have been shown to be of sufficient accuracy to be applied in a forensic context, the low percentage correct classification observed in the determination of biological sex and ancestral origin indicate that these methods should be employed with caution and in full cognisance of their limitations. In the context of the assessment of stature, the low R^2 values repeatedly obtained from the relationship between living stature and metatarsal length indicate that this method should be used only in the absence of other sources of information relating to this characteristic. It is clear from this review of the literature pertaining to the examination of the forensic significance of the foot that further research is required in areas related to the determination of a biological profile, DNA analysis from the bones of the foot and the specific effects of footwear on the process of decomposition and disarticulation.

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