



CAN IT BE AN ACTUAL HUMAN FOSSIL FOOTPRINT? THE "COMBINED METHOD" HELPS TO GIVE AN ANSWER

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ABSTRACT: Recent technological improvements and the growing precision of surveys and analytical procedures together with the growing interest in hominid palaeoichnological traces demand verification of all track-like impressions, especially those which are supposedly human.

Strict analysis and objective interpretations are increasingly necessary for those hollows which have been too hastily recorded as actual human footprints. In some specific environments, such as quarries or other archaeological sites which have been and are still being continuously altered by natural agents (such as eustatic movements, or weathering/aeolian phenomena, or geochemical processes), the number of structures which mimic the shape of human footprints is incredibly high and can lead to false interpretations.

Here we try to improve a successfully used method to re-analyze and reject the actuality of the supposed human fossil footprints from the Valsequillo basin (Mexico) by combining it with well-known and tested forensic methods of gait analysis. We think the new method that we are calling Combined Method (CM), enables scientists to gain a better understanding of whether a hollow on the ground can actually be a human footprint or not, even in cases where not all its contour details or anatomical landmarks are preserved or recognizable.

KEYWORDS: human ichnology, human footprints, pseudo-track analysis.

1. INTRODUCTION

A simple glance at the world-wide hominid palaeoichnological record is sufficient to realize that only a few sites are scientifically studied and exhaustively documented. Other sites are only known through some folk tales or brief mentions in some papers (Avalayra-Arroyo de Anda, 1950; Houck et al., 2009; Lockley & Roberts, 2004; Lockley et al., 2008; Lockley et al., 2009; Lockley & Rodríguez-de la Rosa, 2009; Quevedo-Lara, 1998; Rodríguez-de la Rosa et al., 2004; Rodríguez Asensio-Noval Fonseca, 2012: 226). Furthermore, many other ichnological and/or palaeontological sites such as *Terra Amata* (de Lumley et al., 2011; Goudet-Ducellier, 1987; Hadingham, 1985), *Happisburg* (Ashton et al., 2014), *Vértesszőlős* (Fluck, 2011; Kretzoi&Dobosi, 1990; Bridgland et al., 2006; Visy et al., 2003), *Sierra Tarahumara* (INAH, 2011), *Kenfig Sands* (Bennett et al., 2010), *Rhodes Island* (Bromley et al., 2009; Milàn et al., 2005) and *Bakala Region* (Marquer, 1960) are still enveloped by a dense cloud of doubts about their validity as actual human ichnosites. For these reasons an objective revision of the most ambiguous evidence and unsatisfactory documentation available has made the necessity arise to have a final, complete and scientifically based hominid-palaeoichnology record. The mentioned necessity became stronger after the well-known episode of the Valsequillo Basin (Mexico) where some depressions in the ground were first interpreted as hu-

man and animal footprints (González et al., 2006a, 2006b) and then after further studies, they were shown to be just simple signs left by quarrymen using metallic tools within a quarry area (Morse et al., 2010). The scientific method used to prove and reject the mistaken interpretation was elaborated by a team (Morse et al., 2010; Morse, 2010) taking their stand on the fact that the most important anatomic landmarks of the human foot, although influenced by the structure of the middle-foot and/or by the nature of the ground, cannot significantly change their position from the areas of maximum plantar pressure located within the footprint area. Such positions, as well known, match those in which the depressions on the ground are deeper, i.e. in the areas corresponding to the heel, to the heads of the metatarsal bones I and II and to the hallux. The method by Morse et al. was very innovative because it is based on baropodometric observations and frees any analysis from the strict positioning of anatomical landmarks of the human foot (which are not always visible or preserved) in some fixed geometrical positions and focuses on the relative depths inside footprints, which must be coherent with the displacement vectors of body-weight during walking. Moreover, the deepest zones are enclosed by the contour of the footprint and can be included within an ellipse inscribing the complete foot. In the new scheme of evaluation, 5 main proposed landmarks also seems to go over some eventual trackmaker's deformations capable of misleading scientists (Morse et al., 2010). How-

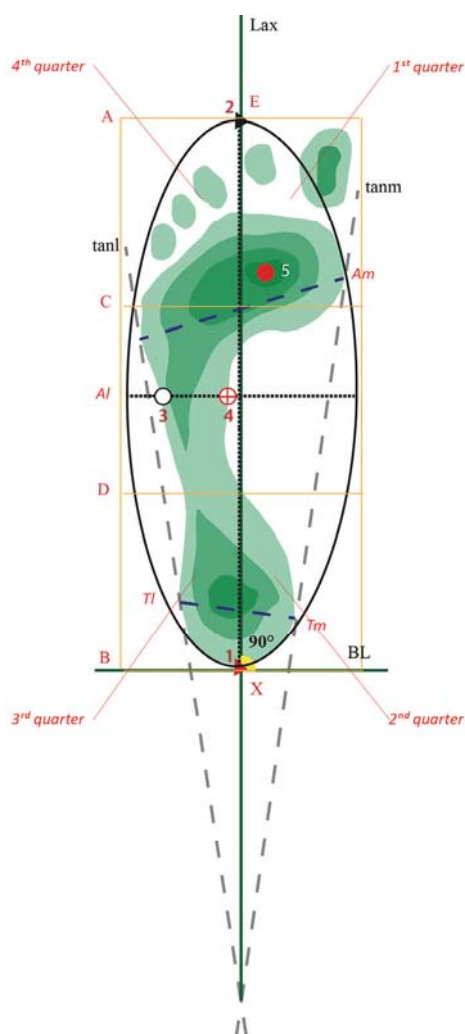


Fig. 1 - The *Combined Method* scheme (Reworking and combination from Wilkinson et al., 1995; Kennedy et al., 2003; Morse et al., 2010).

ever, such a technique to verify human footprints can be applied only on «any potential footprint that would be considered complete, that is heel to toes, without regards to its anatomical definition» (Morse et al., 2010).

Here we try to go beyond this limit and to improve the mentioned method by trying to make it applicable to each footprint-like hollow. For this purpose we elaborated a new method, called "Combined Method" (CM), by combining the described technique with other methods of analysis which have proved successful in forensic environments and which appear easily applicable, i.e. those by Wilkinson et al. (1995), Kennedy et al. (2003) and Berge et al. (2006).

2. THE COMBINED METHOD (CM)

Although based on the same basic principles of the method elaborated by Sarita Amy Morse and her colleagues in 2010 (Morse et al., 2010), the "Combined

Method" (CM) (Fig. 1) is an improvement as it has fewer limitations and can be applied to each depression on the ground, even when its contour is not completely preserved. Furthermore, although with different degrees of approximation, the CM permits the creation and management of a longitudinal axis of the imprint which can be aligned to the major axis of the ellipse designed by the same Morse et al.'s method even when its proximal and/or distal margins are lost. In this way the ellipse including the imprint (*EMor*) can be oriented so that it matches the actual orientation of the potential human footprint and this enables the deepest zones to be located more precisely. Moreover, as the CM can also be applied to some borderline cases each depression can be contextualized within a gait pattern by identifying a well-defined line of progression.

The sharpness of the CM is directly proportional to the amount of available and visible details inside the potential footprint, but it always permits the determination that if at least the hollow can be compatible or not with an actual human footprint. Finally, the *EMor* can be divided into further subsets, which are very useful to identify and to analyze some diseases of the trackmakers' foot (Panarello, 2016). The following is an explanation on how the CM works.

After having checked if the hollow to be studied is located on the former surface of a stratigraphic layer, if all of the geological, chronological, taphonomic and morphostructural conditions of compatibility are fully satisfied (Panarello et al., 2017), it is possible to begin the application of CM by tracing all the visible details of the potential human footprint and locating at least two notable points both on the lateral and medial side. Such points must indicate the widest and the narrowest part of hypothetical footprint's contour. The same points will be indicated as *Am* and *Al* if referred, respectively, to the medial and lateral tips of the hypothetical forefoot (ball zone) and as *Tm* and *Tl* if referred, respectively, to the medial and lateral tips of the hypothetical hindfoot (heel zone). This allows for an initial basic evaluation of the depression because in an actual human footprint *AmAl* is always a greater value than *TmTl*.

If the entire contour of the foot is visible it must be traced according to the scheme by Kennedy et al. (2003) marking the *Convex hull* of the footprint, i.e. the complete contour of the footprint without toe impressions.

So *Am* and *Al* will match respectively, the medial and lateral edges of the ball corresponding to the heads of the 1st and the 5th metatarsal bone. In the same way, *Tm* and *Tl* will respectively match, the medial and the lateral edges of the heel. As a consequence *AmAl* corresponds to the max width of the forefoot and *TmTl* is to the max width of the heel.

By continuing to apply Kennedy et al.'s method (Kennedy et al., 2003) we can draw the medial tangent (*tanm*) to the contour passing through *Am* and *Tm* and the lateral tangent (*tanl*) to the contour passing through *Al* and *Tl*. Such tangents intersect at a point outside the footprint, which is located behind the heel. The bisector of the angle between *tanm* and *tanl* is the longitudinal axis (*Lax*) of the footprint. *Lax* is the real axis of the footprint when its complete contour is visible and it generally

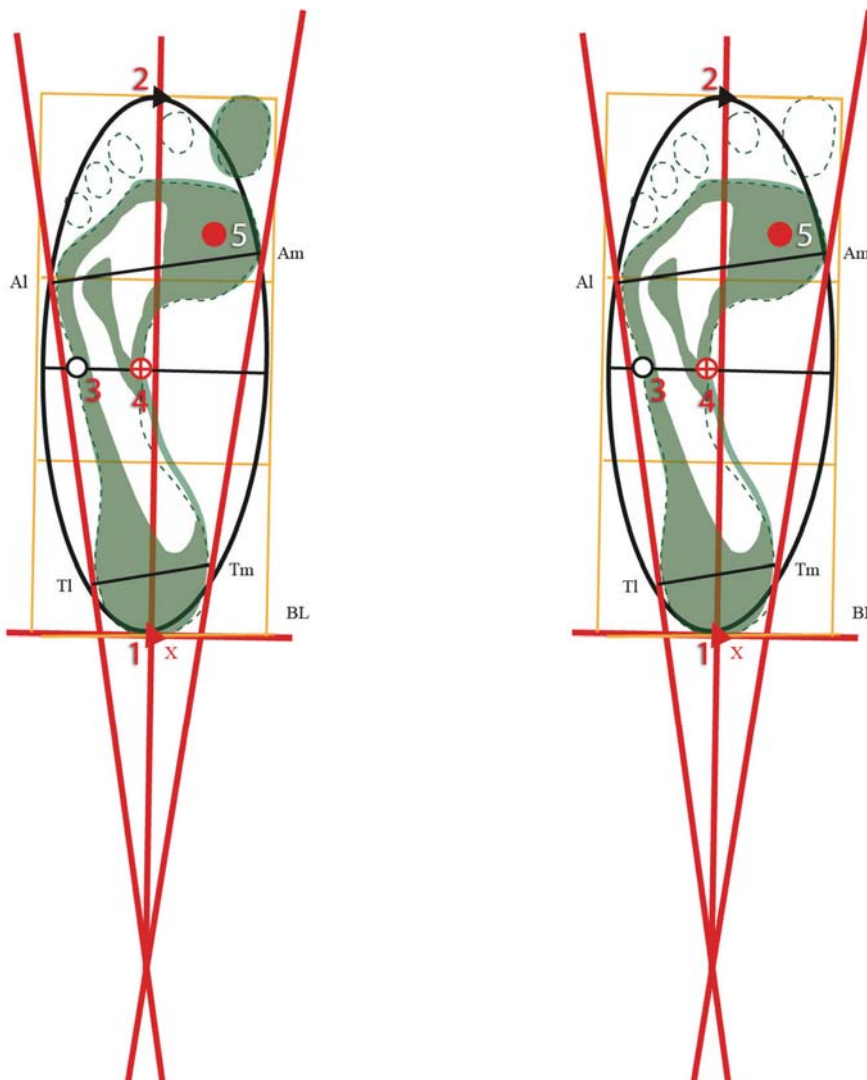


Fig. 2 - Samples of footprints related to case A.

passes through 2nd and 4th toe in a normal foot (D’Août & Aerts, 2008). When the contour of the footprint is not completely preserved, *Lax* must be considered as a virtual axis, which is fully working in the CM, as it never falls out of the zone closed by the 2nd and the 4th toe even when it cannot fully express the angular reality.

In fact, it does not distort the CM scheme since it is not based on specific anatomical positions but rather on areas of compatibility.

Taking into account that the heel-strike is the detail which is almost always present in a human footprint, we thought of choosing it as a basic landmark, its rearmost point crossed by *Lax* as indicated by *X*. Finally, the line crossing *X* and normal to *Lax* was considered as the base-line and indicated by *BL*.

The next steps are the correct positioning of the major axis of the *EMor* so that it matches the *Lax* and specifies the length of the major axis. A further step is to place a variant of the rectangular and tripartite grid (*ReWil*) used by Wilkinson et al. (1995) and by McCrory

et al. (1997) in their methods. Several cases may arise:

Case A (at least the longitudinal contour of the footprint is visible, with or without the imprint of the hallux) (Fig. 2)

This is the luckiest case, because it is very easy to identify the lateral and medial edges, to draw the corresponding tangents, to identify *X* and *BL* and to place the *Lax* making it coincide with the major axis of *EMor*. The only problem to solve is determining the length of the major axis of the *EMor*. If the imprint of the hallux is preserved it is easy to draw the *ReWil* by placing one of its bases on the *BL* and by drawing the other parallel base in such a way that it passes through the most distal point of the footprint which is clearly identifiable on the frontal tip of the hallux. If the imprint of the hallux is not preserved we can determine an approximate major axis length by searching for it among the values in Table 1 or taking into account the dimensional proportions of the foot as indicated by the lengths of the tarsal, metatarsal

Hominid (model)	Epoch (years B.P.)	Average length of the foot (cm)	Source
<i>Australopithecus</i> (Laetoli G-1)	3.6 Ma	~18	Tuttle, 1987; Tuttle et al., 1990.
<i>Australopithecus</i> (Laetoli G-3)	3.6 Ma	~20,88	Tuttle, 1987; Tuttle et al., 1990.
<i>Homo ergaster/erectus</i> (Ileret)	1.52 Ma	~25,8 (range: 21,1-30,5)	Bennett et al., 2009, 2009s; Dingwall et al., 2013
<i>Homo erectus</i> (Roccamonfina)	349-350 ± 3 Ka	~23,0 (range: 22-24)	Mietto et al., 2003; Avanzini et al., 2008; Scaillet et al., 2008; Santello, 2010;
<i>Homo sapiens</i> (Chauvet)	26 Ka	21,4	Garcia, 2005
<i>Homo sapiens</i> (Jeju)	15,161 ± 70 Ka	~19,0 (range: 12-26)	Kim et al., 2009
<i>Homo sapiens</i> (Acahualinca)	2.1 Ka	~20,25 (range: 18,5-22)	Schmincke et al., 2010

Tab. 1 - Reference length and width of the fossil human foot for the definition of the longitudinal axis in the Combined Method (CM).

and phalangeal bones. Such dimensions are, respectively, 51%, 26% and 23% of the total foot length. In *Australopithecus afarensis*, the same proportions are, respectively, the 38%, the 32% and the 30% of the total foot length (Kleinerman-Wood, 2006: 49; Tuttle et al., 1991b). The dimensional values in Table 1 refer to hominids of which at least one fossil footprint has been discovered, measured and verified as actual. Of course, such selection must be made strictly taking into account the chronological age of the potentially trampled surface.

Case B (heel-strike imprint is visible but the distal margin of the footprint isn't preserved) (Fig. 3)

In this second case, while positioning the CM elements, we should take into account that only the heel-strike zone must be considered and a triangle must be identified by placing its vertices in the most lateral point, in the most medial point and in the rearmost point, which must be considered as X. The bisector of the angle whose vertex is X must be considered as *Lax*. The length of the major axis of the EMor can be determined by using Table 1 as in the case A. Also the tripartite schemes used by Wilkinson et al. (1995) and by McCrory et al. (1997) can provide great help in deter-

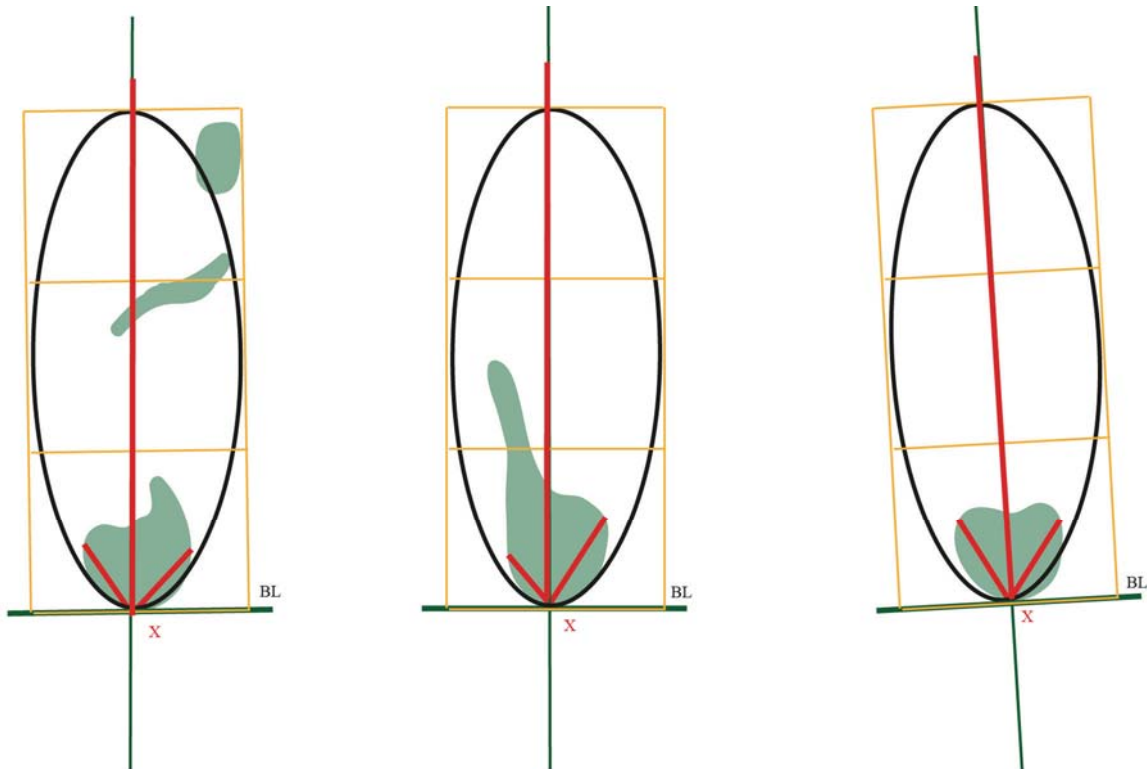


Fig. 3 - Samples of footprints related to case B.

mining the length of the major axis of the *EMor*.

Then the *ReWil* might be positioned taking into account the values in Table 1. Such dimensional values, refer to hominids of which at least one fossil footprint has been discovered, measured and verified as actual. Of course, each choice must be made strictly taking into account the chronological age of the potentially trampled surface. For a wider dimensional range of the foot of contemporary *Homo sapiens*, the huge study by Howard V. Meredith (1944) can be referred to. It must be taken into account that in the case B the degree of approximation of CM is wider.

Case C (at least one toeprint is visible but the proximal margin of the footprint is not preserved) (Fig. 4)

This third case is substantially similar to the second one since the preserved parts are only inverted, but the previously described procedure can be applied only if at least one of the preserved toe prints is the hallux. In such a fortunate case, it is sufficient to invert the procedure of case B by starting from the tip of the hallux to create all the other geometric elements. On the contrary, if only the 2nd and/or the 3rd toe prints are preserved, it is much more difficult to identify all the other elements of the CM since we are in a situation of extreme approximation. In fact, the details of the impression preserved are so few that it is really difficult to find reliable information about both its ichnological reality and/or about its precise location in a gait pattern. In what remains of the imprint only a square-ruler can be applied whose longer side is tangential to the most lat-

eral contour of the toe 2nd or to the most medial contour of the toe 3rd, the shorter and horizontal side of the same square ruler being tangential to the most distal limits of the toe prints. Although with a wide margin of approximation, the vertical side of the square ruler can be considered as *Lax*, so that it is possible to proceed to the application of the values in the Table 1 and to go on to identify the *X* and the *BL*.

When only a few anatomical details are visible, the tripartite scheme used by Wilkinson et al. (1995) and by McCrory et al. (1997) can be a great help in determining the length of the major axis of the *EMor*. Measurement and analysis by the CM isolated footprints or potential footprint in which even less details are preserved should not be attempted.

Case D (both proximal and distal margins of the contour are not visible; only a few traces of the contour are preserved) (Fig. 5)

This is the most complicated case to be analysed as the amount of available detail is poor. As a consequence it is also the case in which the obtained data are mostly approximate. However the main purpose of CM is to make *EMor* most widely applicable and even in this situation it does not seem substantially altered, but let us see how to proceed. In the footprint area we must consider as *Am* and *Tm*, respectively, the most medial edges of the preserved contour of the ball-zone and the heel-zone. Similarly, we must consider as *Al* and *Tl*, respectively, the most lateral edges of the preserved contour of the ball-zone and of the heel-zone.

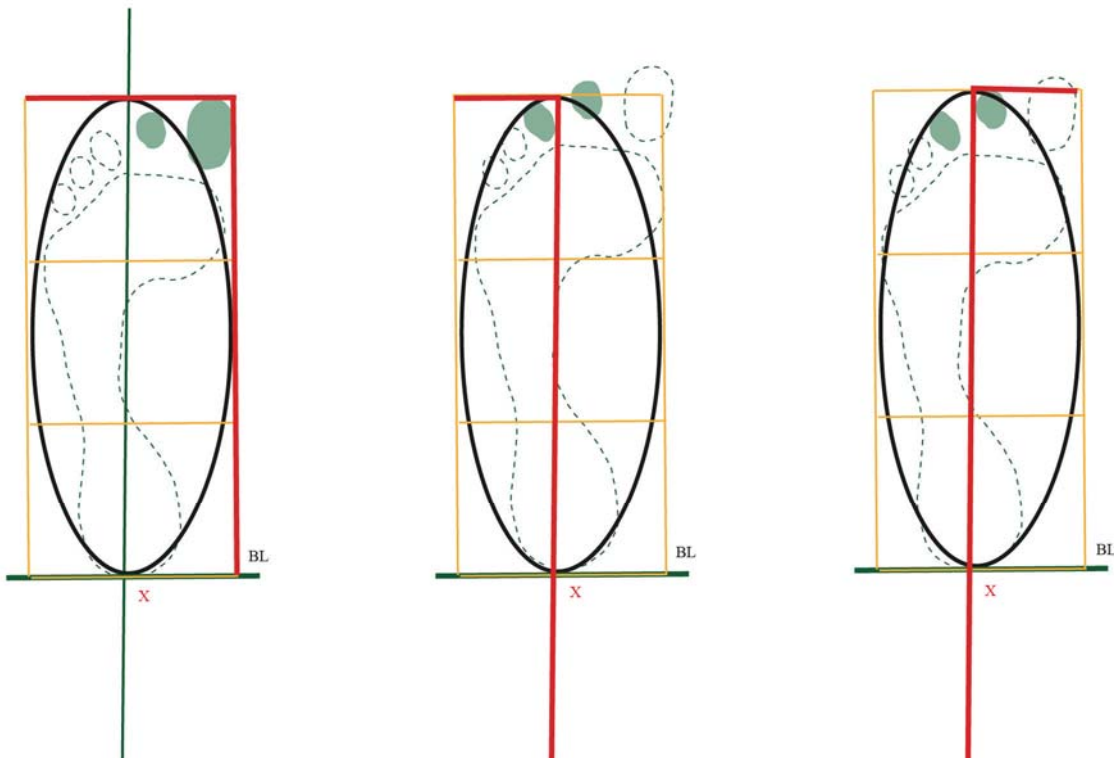


Fig. 4 - Samples of footprints related to case C.

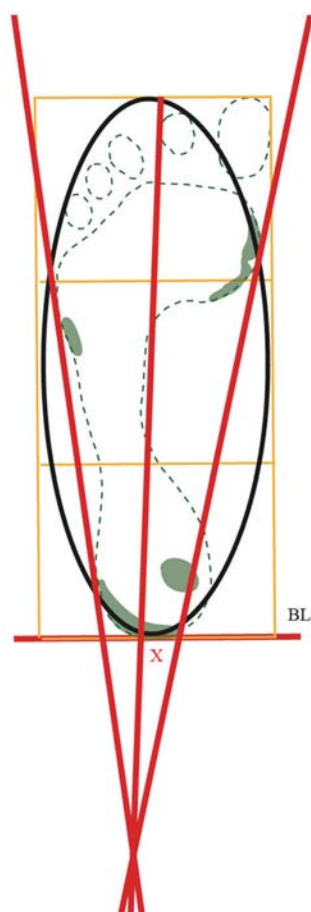


Fig. 5 - Samples of footprints related to case D.

This makes us able to draw a convex hull of the potential footprint and to determine its *Lax* as already carried out in case A. Both of them, though approximate, do not significantly alter the framework of the depressions inside the footprint area. So, it is sufficient to draw the perpendicular to *Lax* passing through the rearmost point of the heel-zone to identify point X. Now we can use Table 1 to determine the length of the major axis of the *EMor* and, consequently, all the other necessary details of the CM scheme. As in preceding cases an additional aid can be given by the tripartite scheme used by Wilkinson et al. (1995) and by McCrory et al. (1997).

Case E (no part of the contour is preserved; only a displacement rim is visible)

In this last case we must be fully aware that we are working on the extreme border of reality and that the only instance in which we analyze the potential footprint is in the presence of a displacement rim in its total structure. Such a rim, as well-known, can be created only by trampling a surface that has yet to be solidified. Nevertheless we must be extremely prudent while analyzing details taking into account that the displacement rim could mean only that the same hollow is a true imprint and not also that it is an actual human footprint.

Of course, if the footprint-like depression is coordi-

nated into a gait pattern the possibility of it being an actual footprint increases significantly.

To apply the CM we inscribe the general hollow marked by the edge of the expulsion rim in the most narrow rectangle that can contain the entire depressed area. So the middle longitudinal line of the rectangle can be considered as the *Lax* and its length matches the major axis of the *EMor*. Of course, the *BL* is the base of the same rectangle. As above, here too we can apply the tripartite scheme used by Wilkinson et al. (1995) and by McCrory et al. (1997) to determine the length of the major axis of the *EMor*.

On the basis of the described geometric constructions 5 basic landmarks should be identified:

- Landmark 1: The point of coincidence on the base-line (*BL*), between the rearmost point of the heel and the lowest point of the major axis of the *EMor*.
- Landmark 2: The highest point of the major axis of the *EMor* located on the parallel to the base-line tangent to the distal point of the most protruding toe print.
- Landmark 3: The point of intersection between the parallel to the base-line passing through the midpoint of *Lax* and the lateral contour of the footprint.
- Landmark 4: The point of intersection between the parallel to the base-line passing through the midpoint of *Lax* and the medial contour of the footprint.
- Landmark 5: The point of maximum pressure inside the footprint area.

3. IN-FIELD EXPERIMENTS

Although the CM is substantially a winning combination of methods (Wilkinson et al., 1995; Kennedy et al., 2003; Berge et al., 2006; Morse et al., 2010), which have been widely and successfully tested, we think that some supplementary specific experimentations in the field of the CM can be useful to verify its reliability and also to show its limitations. For this purpose, we selected two trackmakers (an adult male and an adult female) with known anthropometric characteristics and diseases and we let them walk along different substrates without conditioning their normal walking. The male trackmaker walked on a sandy ground, while the female walked on uneven and chaotic matter made up of mud and gravel, and on another surface consisting of a cement mixture. Then we surveyed the footprints they left and we analyzed them by CM. In all three cases the depth areas inside the footprints were found in the expected sectors of the *EMor*. Moreover, in the case of the female trackmaker, the analysis of the contour lines of the footprints allowed us to detect and to highlight the disease for hallux valgus she had already declared.

All examined footprints proved that CM always works but also pointed out that the variability of the substrate can heavily affect the dimensional range of the same footprints. This suggests extreme caution while making any estimation about the body of the trackmaker starting from his fossilized footprints.

Finally, we successfully tested the *Combined Method* on an actual human fossil footprint, which has

FIGURED MODEL	Figure	N. of images	Camera Model	Image Resolution	Focal Length	Error	Resolution
Experiment on Sea-Sand	Fig. 7,c	53	Canon EOS 550D	5184 x 3456	18-20 mm	0,652527 pix	0.00274447 m/pix
BF_Footprint N. 5	Fig. 8,a	12	Canon EOS 550D	5184 x 3456	32-40 mm	0.523982 pix	0.0007944 m/pix
BF_Footprint N. 6	Fig. 8,b	12	Canon EOS 550D	5184 x 3456	32-40 mm	0.523982 pix	0.0007944 m/pix
BF_Footprint N. 7	Fig. 8,c	8	Canon EOS 550D	5184 x 3456	40mm	0.514934 pix	0.000707582 m/pix
BF_Footprint N. 8	Fig. 8,d	10	Canon EOS 550D	5184 x 3456	40mm	0.568009 pix	0.000642572 m/pix
Experiment on Cement Mixture	Fig. 11,c	68	Canon PowerShot G9	4000 x 3000	7,4-21mm	0.474277 pix	0.00208673 m/pix
SMZ2_Footprint N. 6	Fig. 12,a	68	Canon PowerShot G9	4000 x 3000	7,4-21mm	0.474277 pix	0.00208673 m/pix
SMZ2_Footprint N. 7	Fig. 12,b	68	Canon PowerShot G9	4000 x 3000	7,4-21mm	0.474277 pix	0.00208673 m/pix
Experiment on mud and gravel	Fig. 15,c	39	Canon PowerShot G9	4000 x 3000	7,4mm	0.510538 pix	0.00208673 m/pix
SMZ2_Footprint N. 3	Fig. 16,a	15	Canon PowerShot G9	4000 x 3000	7,4-9,036mm	0.617274 pix	0.00111644 m/pix
SMZ2_Footprint N. 4	Fig. 16,b	15	Canon PowerShot G9	4000 x 3000	7,4-9,036mm	0.617274 pix	0.00111644 m/pix
SMZ2_Footprint N. 5	Fig. 16,c	15	Canon PowerShot G9	4000 x 3000	7,4-9,036mm	0.617274 pix	0.00111644 m/pix
SMZ2_Footprint N. 6	Fig. 16,6	15	Canon PowerShot G9	4000 x 3000	7,4-9,036mm	0.617274 pix	0.00111644 m/pix

Tab. 2 - Parameters of the photogrammetric models.

been dated around 350 Ka B. P. (Mietto et al., 2003; Avanzini et al., 2008).

The photogrammetric measurements were taken using an SLR camera CANON EOS 550D equipped with lens CANON EF-S 18-200 mm and a compact camera Canon Powershot G9. Developments, measurements and calculations of three-dimensional models, as well as maps derived therefrom, were made using the software AgisoftPhotoScanProTM (ver. 0.9.0 build 1586) and KitwareParaViewTM (ver. 3. 98.1.64) and the details of each photogrammetric model are shown in Table 2.

We think that the field experimentations we present here are good examples to show that CM is effectively able to reveal if a hollow on the ground can be an actual footprint or not. Furthermore, the CM proved effective in any weathers and is capable of revealing some deformations of the foot if present.

Sea sand

The experiment was carried out in a place of the Tyrrhenian shore at Scauri, a small city located in Central Italy (province of Latina; N41° 15.010' - E13°42,941') (Fig. 6). The Trackmaker (B.F., male, aged 54, 1,65 m tall, and 66,5 Kg weight) said he had suffered some years ago from a double fracture of the left anklebone with detachment of the cartilaginous joints. During the experimentation, he walked barefoot for a distance of 8 meters. The footprints he left were 14, of which 7 relate to the right foot and 7 to the left foot. The data concerning the gait, however was measured only in the central part of the trackway and refers to the tracks from 5 (left) to 8 (right) (Fig. 7, Fig. 8), in order to avoid any additional variables due to acceleration or

deceleration. The average measured stride is approximately m. 1,175. The average length of the measured foot is m. 0,27. The average width of the track is about 38 cm. The estimated stature measured starting from footprints' dimensions almost perfectly matches the effective one by applying a ratio of 16,4%, which is in perfect harmony with an extremely pliable substrate that guarantees that the footprint is dilated both in length and in width compared to the actual size of the foot. Sea sand, which is composed of very fine grains, has proved to the most receptive substrate, capable of preserving a detailed impression giving exhaustive anatomical and biomechanical data. The details are more evident in



Fig. 6 - Scauri Beach (Central Italy) - Location of the experiment on sea-sand (trackmaker: B.F., male).

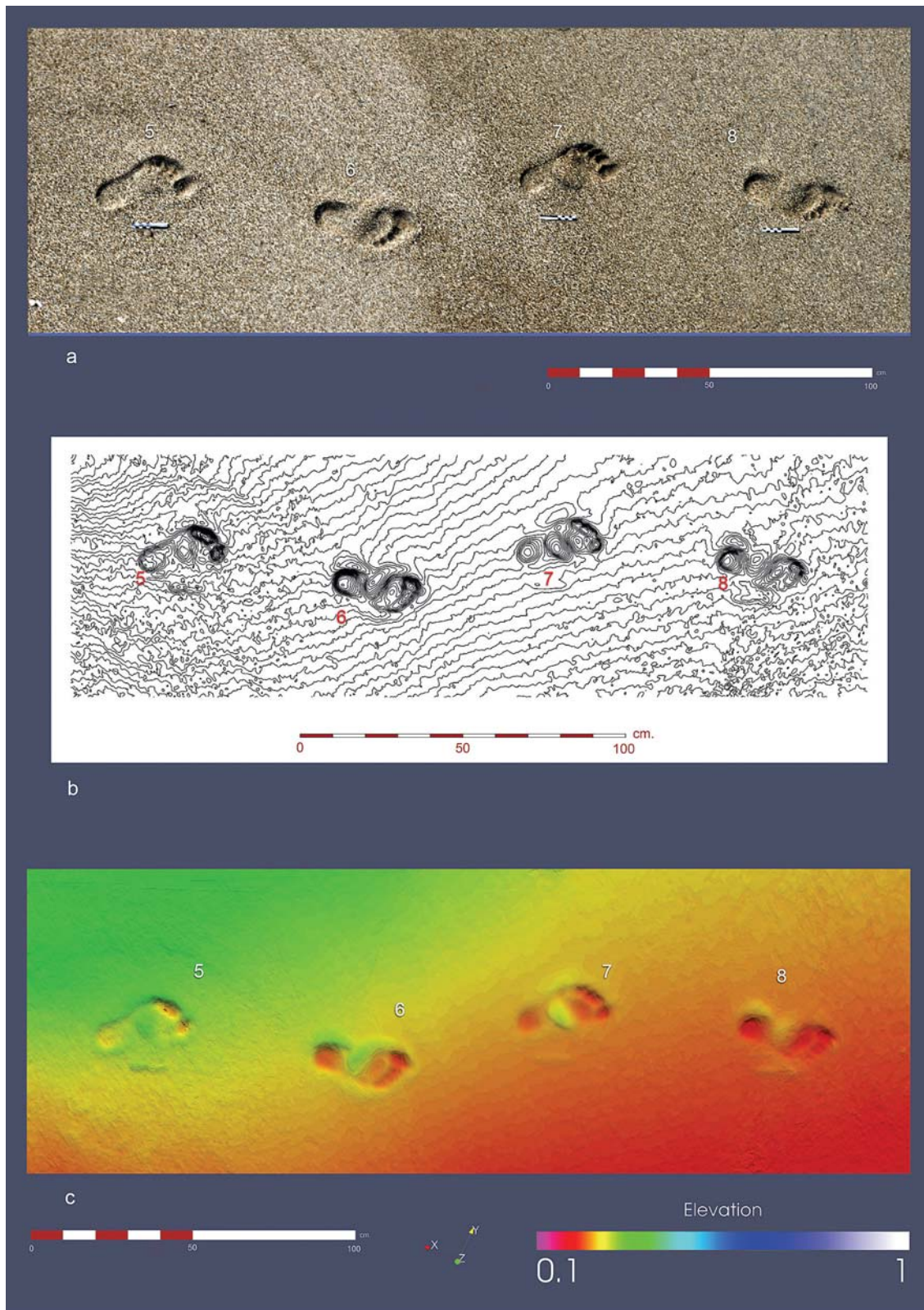


Fig. 7 - Experiment on sea-sand: the analysed footprints among those left by the male trackmaker B. F. (a: zenithal photography; b: contour lines (1mm); c: depth map).

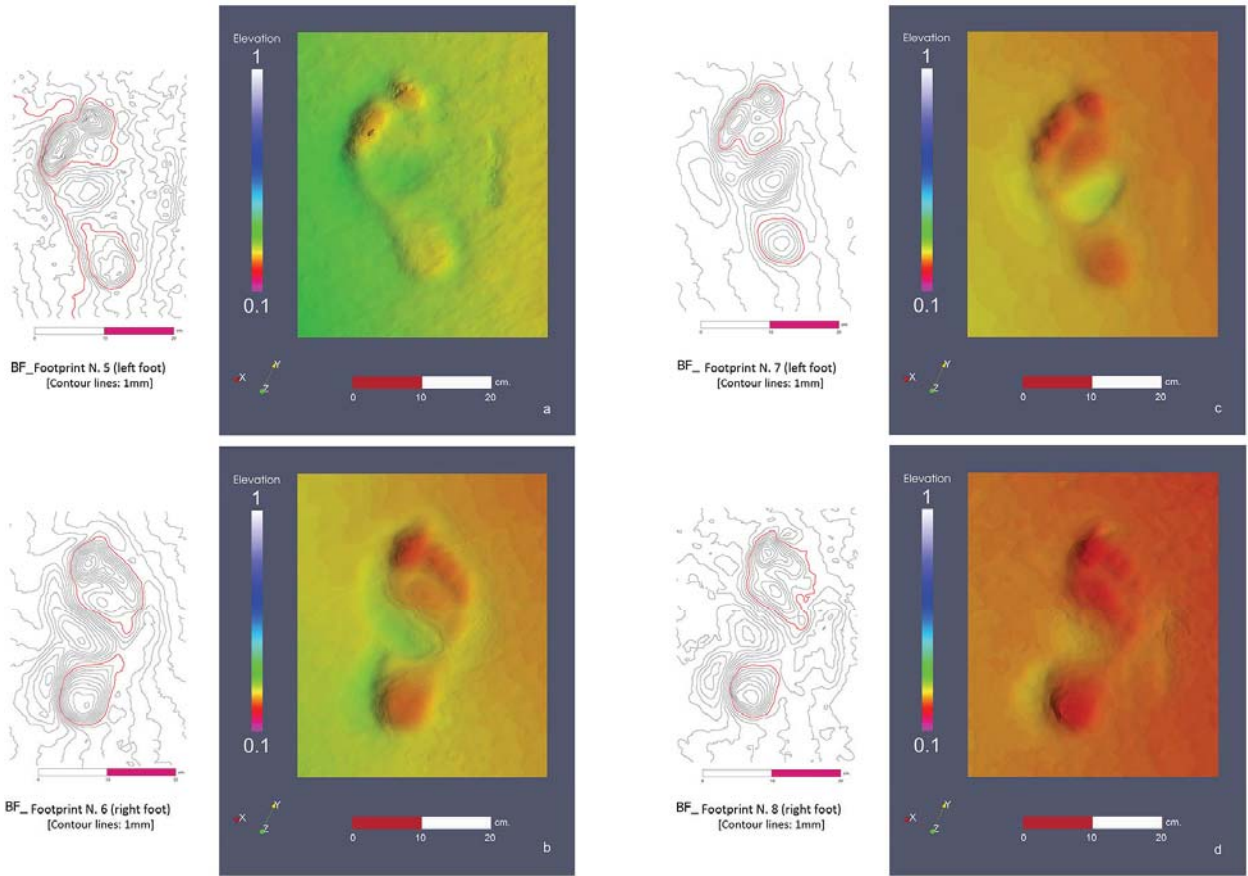


Fig. 8 - Experiment on sea-sand: details of the four considered footprints.

places where marine sand also has slightly slimy component. It is also very interesting to note that a large amount of sand is pushed up corresponding to the medial longitudinal arch area and this makes evident that body balance while walking is searched and found in the lateral area of the foot. The backwards movement of the toes is also evident as they try to grip the ground and

this creates a very pronounced discontinuity between the distal part of the forefoot (which assumes precisely the rounded shape of a pillow) and the proximal part the toe depressions, which are aligned with the hallux depression along an anteromedially oriented direction. Finally, the foot angle, i.e. the angle measured between the tread and the axis line of progression, shows that the

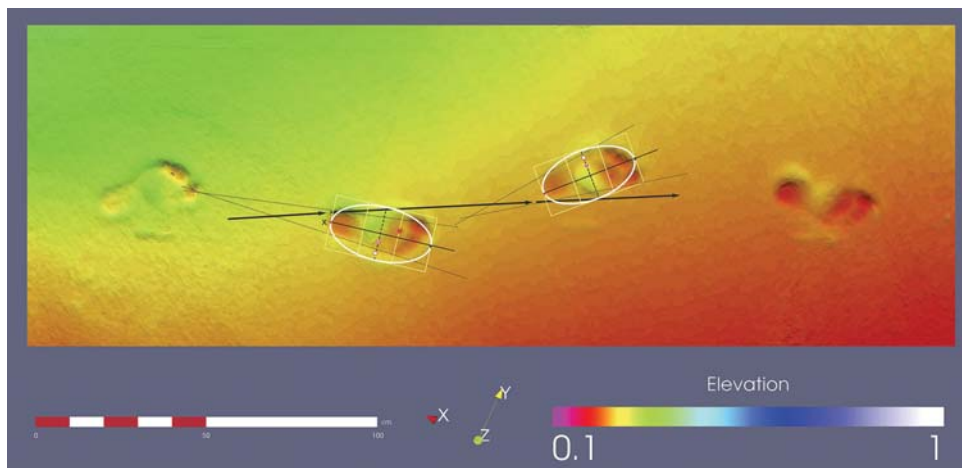


Fig. 9 - Experiment on sea-sand: the *Combined Method* applied on the considered stretch of trackway.

left foot (18°) is more everted than the right (16°), which could be reminiscent of the trauma fracture in his left foot, which, although it has perfectly healed, may have left a trace in the gait pattern. Finally, in all of the footprints, which are magnificently preserved, all the characteristics of the human foot are fully recognizable, i.e. 1) a wide and well-rounded heel pad; 2) a well-shaped, narrow and raised medial arch; 3) a well-defined forefoot with a well characterized ball; 4) the presence of occasional ridges proximal to the positions of the heads of the 1st and the 2nd metatarsal bones; 5) maximum extension in the distal zone of the ball pad which is rightly located in correspondence of the position of the 2nd toe; 6) well defined and separated impressions of pad and tip of the hallux; 7) well defined impressions of lateral toes (Meldrum et al., 2011). Specifically referring to the CM application, all the landmarks are in their correct position (Fig. 9).

Cement mixture

The experimentation was carried out during the casting of a pavement, on a specially leveled surface (Fig. 10). The substrate was composed of a mix with a very high percentage of cement, enriched with potassium and a plentiful quantity of river gravel. The experiment was carried out in the rain so the degree of wetting was very high and gave the consistency of an almost muddy matter with continuous collapse of the sidewalls of the footprints after a lifting of the foot.

The Trackmaker was a female (S.M.Z., 45 years old, 1,52 m tall and 55 Kg weight) who is suffering from hallux valgus on both feet. During the trial, she walked barefoot along a distance of 10 meters on an almost planar and extremely yieldable ground. She left a total of 17 footprints (8 relate to her right foot and 9 relate to her left foot). However, to avoid any bias from braked or accelerated gait, all data was recorded only in the central part of the trackway and refers to the footprints from 6 (right) to 9 (left) (Fig. 11). The average stride measured is approximately m. 1,10. The measured average length of the foot is about m. 0,20. The estimated stature starting from the footprints' length almost perfectly matches the effective one if we apply a 13,2% ratio. This is easily explainable if we consider that the soft matter of the substrate always collapses inside of the impression after the foot pressure and its consequent lift which causes extremely irregular contours and frames which, in any case, are less long and/or less wide than the real ones. The average angle of the left foot, with respect to the line of progression, is equal to $6,5^\circ$ while the average angle of the right foot is equal to $7,5^\circ$. The average measured width of the track is about 25 cm.

It is worth nothing that only footprint n. 6 and n. 7



Fig. 10 - Location of the experiment on cement mixture (trackmaker: S.M.Z., female).

are completely and objectively measurable. The footprint n. 6 (right foot) (Fig. 12), although narrow and elongated, preserves an evident medial concavity, which has its own center in the central third of the total length of the footprint. Furthermore, if we apply the *EMor* on it (Fig. 13), we can notice that the landmark on the key of the vault of the medial longitudinal arch fully respects the criterion of Berge et al. (2006) as it falls in a higher position than the forefoot and the rear foot impressions. Finally - although partly covered by the collapse of the medial wall of the cavity - it is clearly visible, within its contour, the protrusion of the 1st metatarsal head. Also on the lateral side, the movement towards the intermotal soft wall has reduced the width of the midfoot, but has not completely erased the anatomic details of the human foot. The forefoot, as was logical to be expected, is evident, as well as the most proximal part of the depression of the hallux.

Another important specimen is the footprint n. 7 (left foot) (Fig. 12), which is the clearest and most readable one. It has an extended displacement rim, which is more evident on the lateral margin. Here the sidewalls

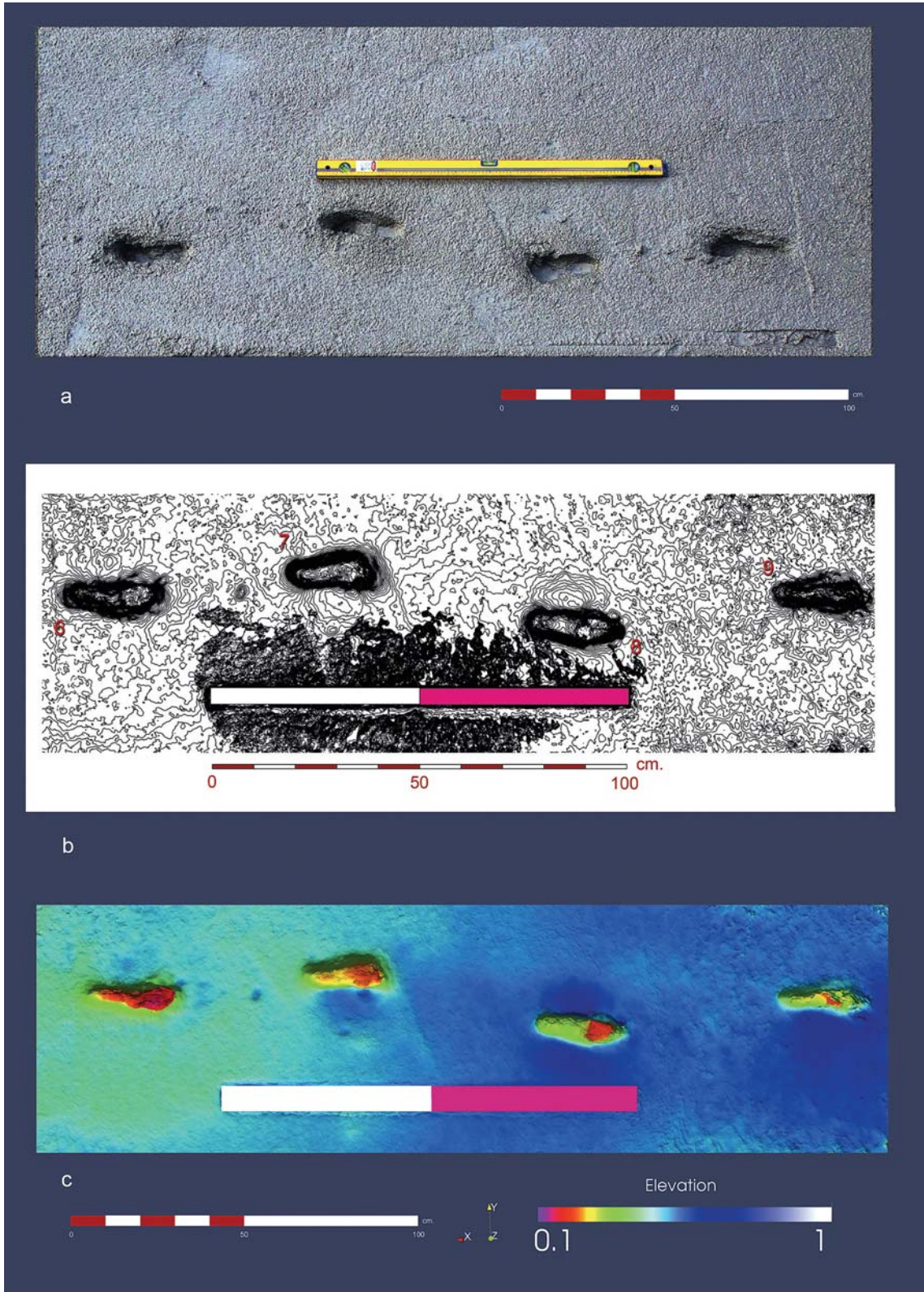


Fig. 11 - Experiment on cement mixture: the analysed footprints among those left by the female trackmaker S.M.Z. (a: zenithal photography; b: contour lines (1mm); c: dept-map).

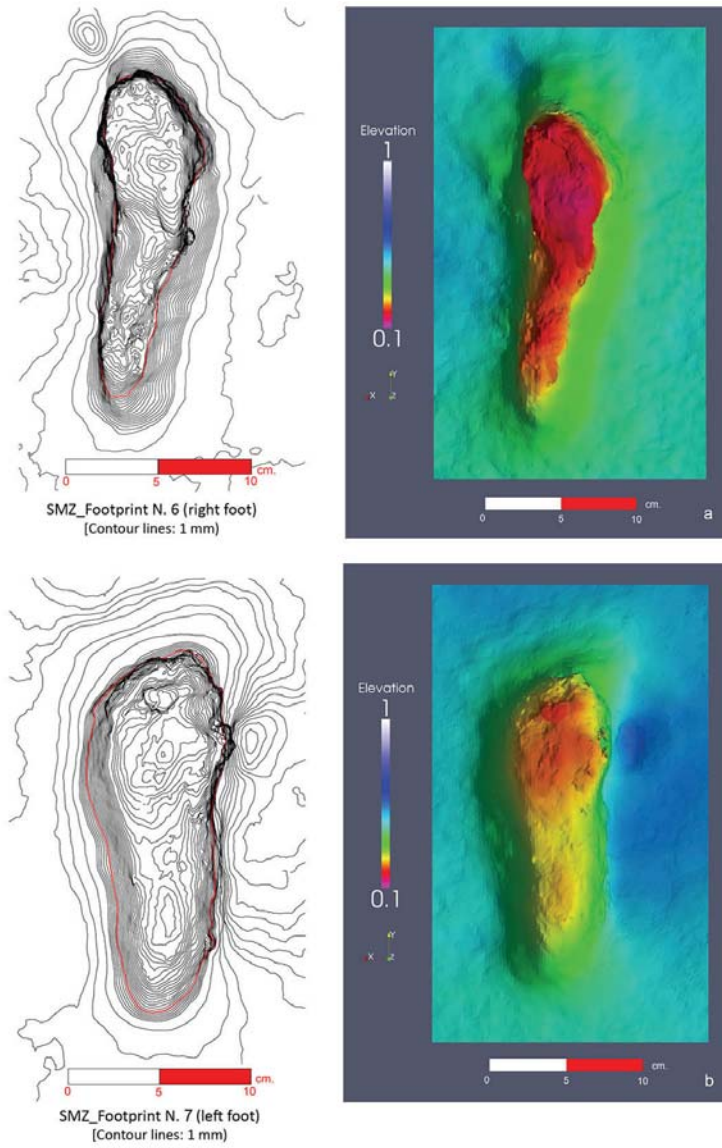


Fig. 12 - Experiment on cement mixture: Details of the two best surveyable footprints among the four considered ones.

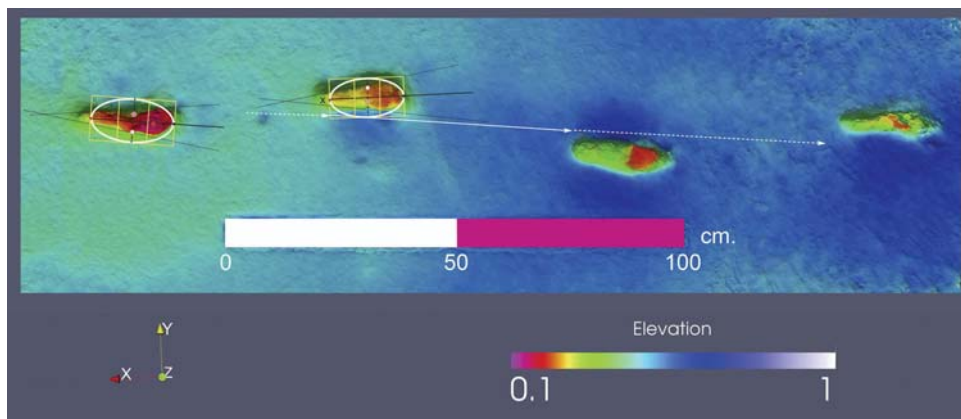


Fig. 13 - Experiment on cement mixture: the *Combined Method* applied on the considered stretch of trackway.

had only minor failure meaning every detail of the shape of the foot is well recognizable. The footprint inclusion within the *EMor* diagram has further highlighted the correct anatomical position of maximum pressure areas and so the impressions of the heel and the forefoot with the hallux and 2nd toe are very evident. Medially, likewise the protrusion of the head of the 1st metatarsal bone is very evident, confirming disease of hallux valgus as declared by the experimental trackmaker before starting her walking.

Within the footprints n. 8 (right foot) and n. 9 (left foot), the details are less clear so that the *Emor* is not easily fixable. However, in both cases the areas of maximum pressure are evident inside the footprint and are located in the third medial distal part. Such evidence is fully compatible with those of the same kind which are better preserved in the other footprints (Fig. 13). Finally, the frameworking within an ichnological pattern respecting human gait-standard is clearly constructible as one could expect since the trackmaker is definitely human.

Mud and gravel

The experiment was carried out on a small area created by the outflow of precipitated waters during heavy and prolonged rainfall. The transported debris are laid on a thick muddy bottom, creating a composite matter, which is muddy and extremely plastic in depth and has an uneven, porous and grainy surface.

The emplaced layer is about 9 cm thick, while its grainy surface is only a few millimeters thick (Fig. 14).

We chose this kind of deposit to analyze the response of such a chaotic matter to foot pressure during walking.

The trackmaker is the same used for the experiment on cement mixture (SMZ, female, 45 years old, 1,52 m tall, 55 kg weight, with a declared disease from hallux valgus on both feet) and she walked barefoot along a stretch of about 3 meters, leaving 7 footprints (4 relate to the right foot and 3 relate to the left foot).

As in previous cases, to minimize the distortion due to an eventual mental conditioning for the initial acceleration and the final braking, only four footprints in succession have been considered, that is the most central ones, from the footprint N. 3 (right) to the footprint N. 6 (left) (Fig. 15).

The average angle of the left foot, compared to the line of progression, ranges from -2° to -5° revealing a tendency to intoflex the foot overcoming the line of progression, perhaps forcing the pronation in the search for balance during walking on such unstable ground. On the contrary, the average angle of the right foot is quite constantly 4° . The average width of the tracks is about 18 cm. The average measured stride is approximately m. 0,73. The average length of the measured foot is about m. 0,21. The estimated stature starting from footprints length almost perfectly matches the actual one by



Fig. 14 - Detail photo of the matter used for the experiment on mud and gravel (trackmaker: S.M.Z., female).

applying a 13,8% ratio.

Also in this case, the extremely yieldable substrate influences the actual size of the prints, but without erasing the anatomical features of the foot.

The footprint n. 3 (right foot) (Fig. 16) is very light as it was left in a small area where the mud layer was thinner. Although the displacement rim is barely perceptible in the lateral side area, the hollow of the forefoot is perfectly recognizable and clearly shows the declared disease from hallux valgus on both feet. The cavity of the hallux is also easily recognizable, especially in its proximal part.

The footprint n. 4 (left foot) (Fig. 16) is recognizable in all its parts and preserves the signs of high pressure in the forefoot area, especially in correspondence with the head of the 1st metatarsal such highlighting the mentioned disease from hallux valgus. In addition within the footprint n. 4 area a strange accentuation of depth in the medial side of the ball is also evident. This is due to the major pliability of the ground at that point that was instinctively compensated by the trackmaker with a more pronounced anteromedial pronation.

Footprints n. 5 (right foot) and n. 6 (left foot) (Fig. 16) are those which preserve the clearest anatomic details of the human foot and in both of them, the depressions of the heel, medial longitudinal arch, forefoot, toe depressions and big toes were perfectly identifiable. The footprints n. 3 and n. 5 are slightly intoflexed with respect to line of progression, but they do not show a significant depth in their medial distal area. This is due to greater compactness of the ground at that point and also to a more secure and steady pace. Finally, both footprints show evidence of hallux valgus, represented by a pronounced protrusion medially oriented of the ball in correspondence of the head of the first metatarsal bones.

Also on this very heterogeneous ground all fixed

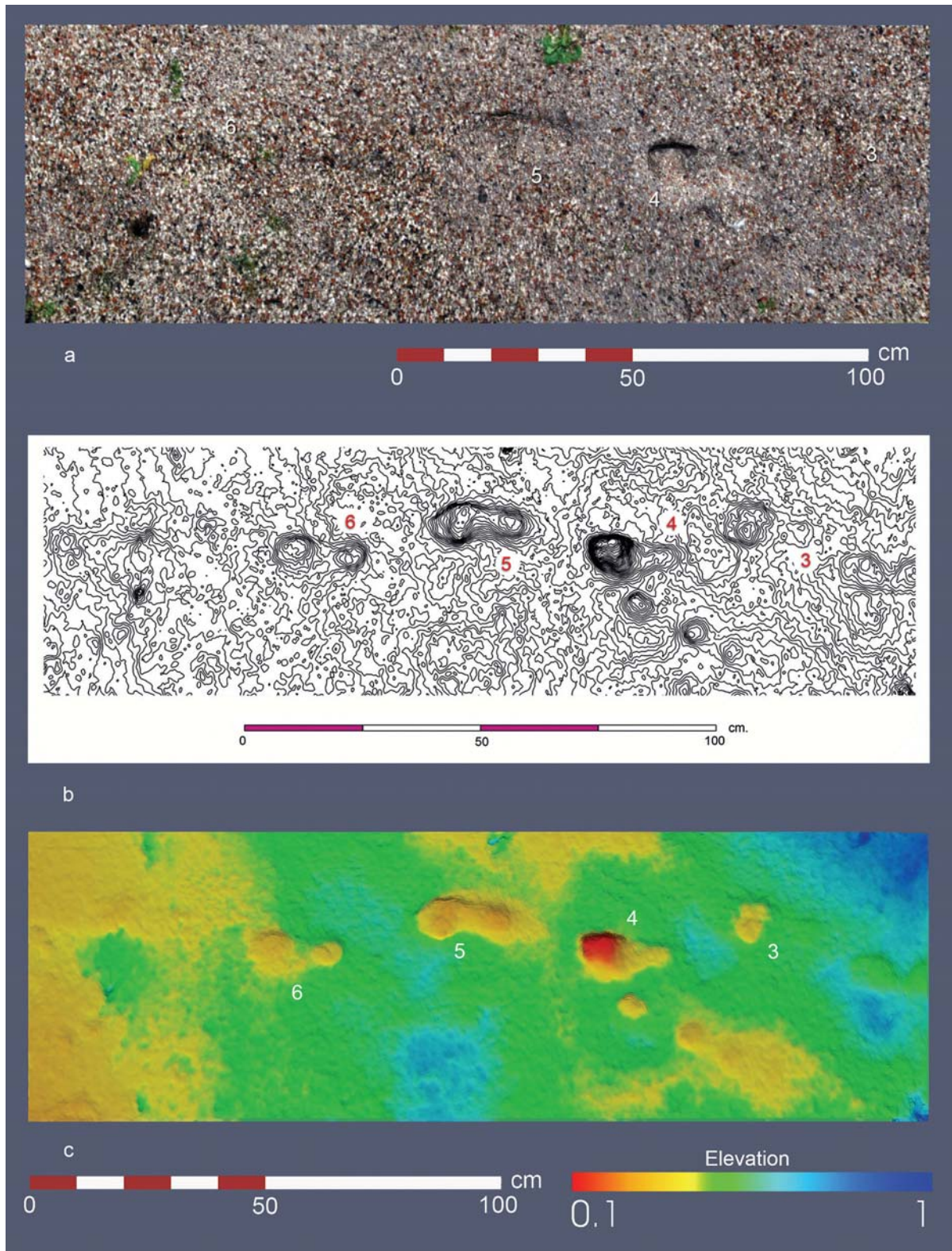


Fig. 15 - Experiment on mud and gravel: the analysed footprints among those left by the female trackmaker S.M.Z. (a: zenithal photography; b: contour lines (1mm); c: dept-map).

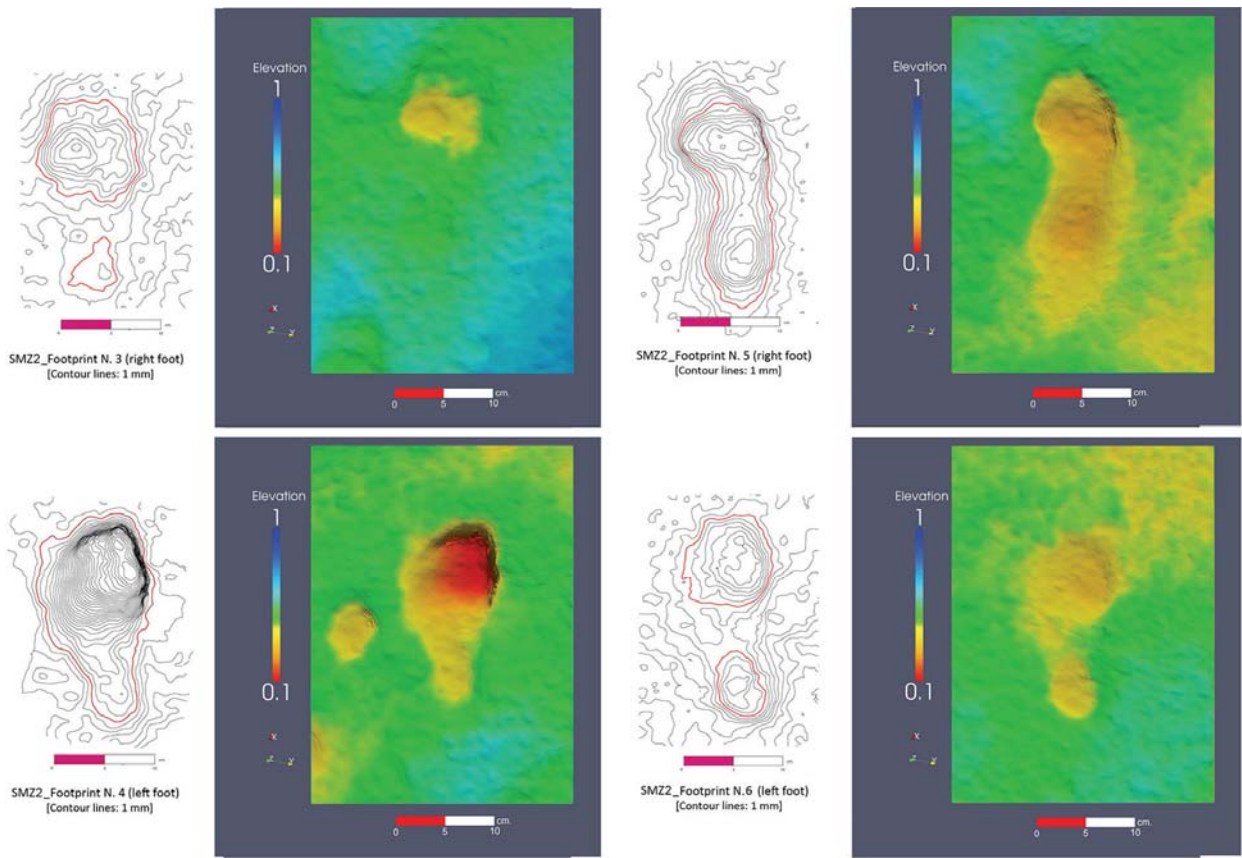


Fig. 16 - Experiment on mud and gravel: details of the four considered footprints.

landmarks fall in the correct anatomic areas within the fixed *EMor* (Fig. 17)

Finally, we must observe that the length of the step and of the stride seem to be influenced more by a sort of consciousness of the brevity of the walkable route than by the instability of the ground.

Actual human fossil footprint

We also applied the Combined Method on one of the so-called "Ciampate del diavolo" ("Devil's Trails"), i.e. on one of the well-known actual middle-Pleistocene human footprints found on the north-eastern slope of the Roccamonfina volcano (Central Italy) (Mietto et al., 2003; Avanzini et al., 2008).

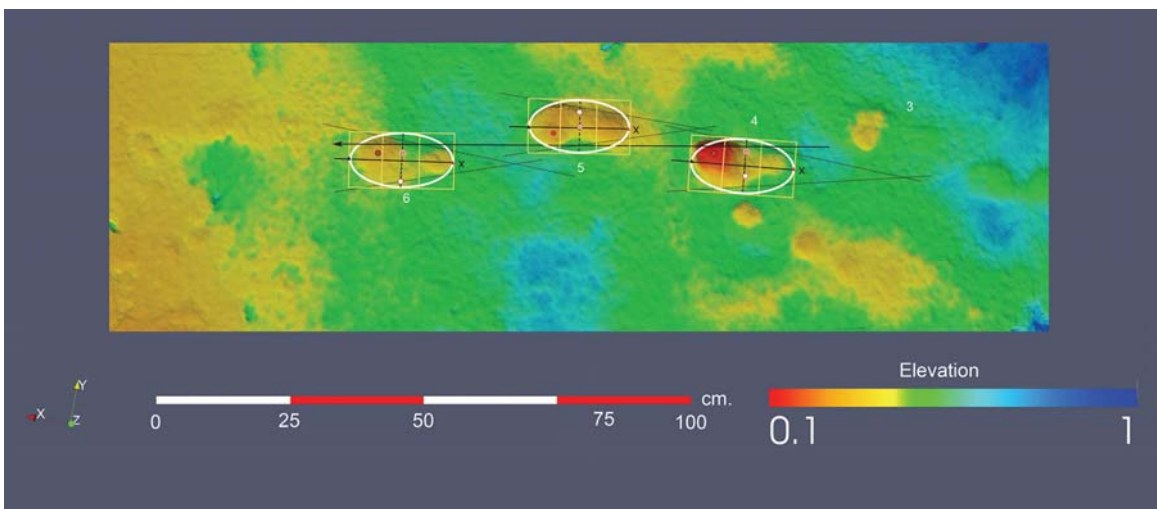


Fig. 17 - Experiment on mud and gravel: the *Combined Method* applied on the considered stretch of trackway.

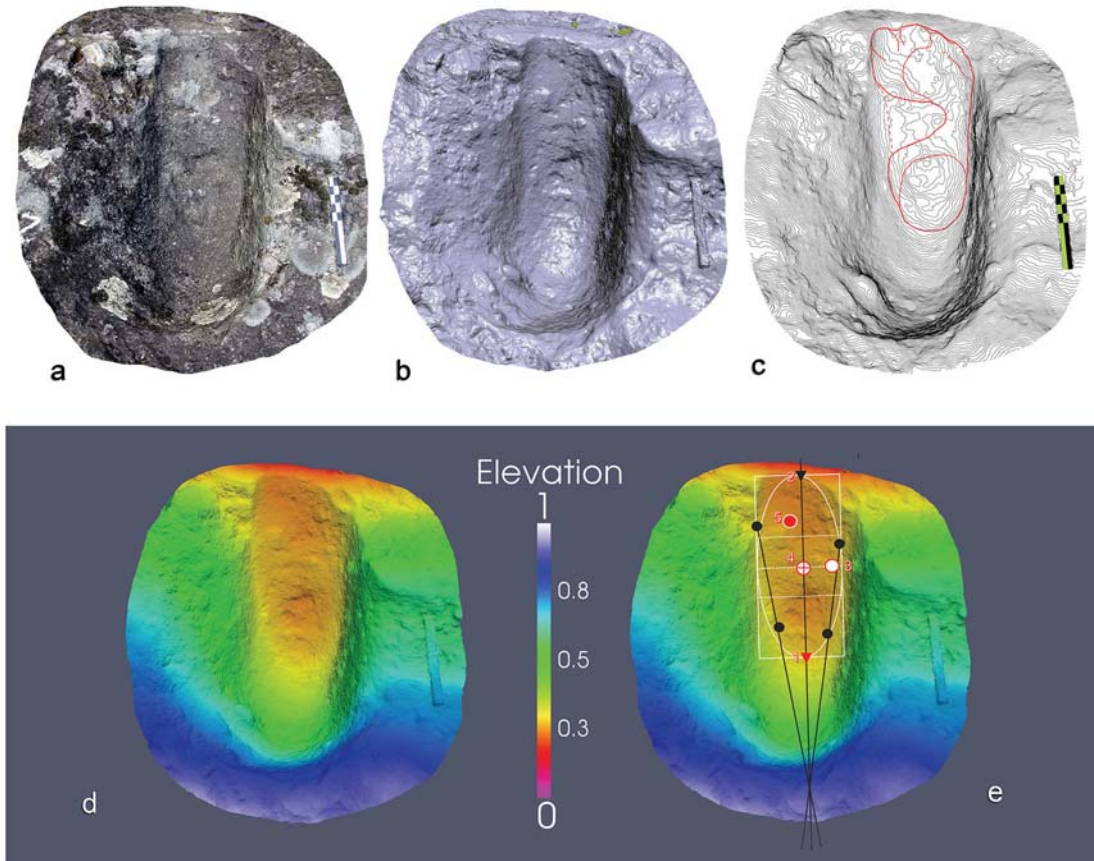


Fig. 18 - Roccamonfina Footprint - "Devil's Trails" - A25 (a: zenithal photography; b: solid surface; c: contour lines (1 mm); d: depth map; e: depth map with *EMor* applied).

We chose for this purpose the footprint A25, which is one of the best preserved and we were soon able to observe that also in this case the CM works very well. In fact, although the footprint is located on a steep slope, all the CM landmarks fall in their correct positions so confirming what we already knew, i.e. that the considered footprint was left on a soft slope by a right foot of an our ancestor who lived around 350 Ka B.P. (Scaillet et al., 2008; Santello, 2010). Within the footprint's contour and using the CM scheme the imprints of the heel-strike zone are clearly visible, like those of the medial longitudinal arch, forefoot and hallux.

All of them match perfectly with the anatomic landmarks where one would expect to find them (Fig. 18).

4. DISCUSSION AND CONCLUSIONS

The schemes and landmarks of the *Combined Method* allow us to scientifically evaluate the precise positions of the most depressed areas within the *EMor* area according to Morse et al.'s method (Morse et al., 2010) and according to the anatomical features of the human foot. It is widely known that the depressions on the bottom of a human footprint can perfectly reproduce the movements of the lower limbs and mainly of the feet during a gait cycle, therefore we should expect to local-

ize the deepest area of the foot in the geometrical zones which the body weight passes through in order to be able to say that a depression is an actual footprint or not. Specifically, the deepest depressions must be located at least in the heel-strike zone, in the zone of the heads of the 1st-2nd metatarsal bones and in the hallux zone (Day & Wickens, 1980; Schmid, 2004; Meldrum & Hilton, 2004; Klenerman & Wood, 2006; Raichlen et al., 2010; Morse et al., 2010; Bennett & Morse, 2014; Meldrum et al., 2011; Dingwall et al., 2013). So it is very important that after the application of the CM at least the landmarks 1 and 5 do not fall, respectively, outside quarters 2-3 (both of the feet) and outside quarter 1 (left foot)/quarter 4 (right foot) of the *EMor*. Similarly, landmark 4, which corresponds to the vault of the plantar arch, has to be always at a higher level than those of all other landmarks as well pointed out by Berge et al. (2006). If some disease or malformation of trackmaker's foot is supposed, it must be present in more than one imprint of the same foot before it can be considered as authentic (Morse, 2013; Bennett & Morse, 2014; Panarello, 2016 and quoted bibliography).

Finally, we think using the *Combined Method*, which is a combination of other already known and well-tested methods, is a significant breakthrough and certainly be considered as an important improvement. It is

clearly evident, its easiness of application and its capacity to be applied practically to each hollow or depression on the ground, even to those in which no anatomical detail is visible. As it is based on the depressions created by the displacement substrate as the human foot ambulates on a soft ground, it is closely linked to the anatomy of the human foot. The CM is free from strictly located positions of the anatomic features of the foot within the bottom of the footprint and is more closely linked to the motion vector of center of mass and of body weight during the gait cycle. Perhaps the CM alone is not able to say if a depression on the ground is an actual footprint or not, but it is certainly able to say if the depression is not an actual footprint and/or if it is at least compatible with a human footprint.

The CM is much more accurate and useful if applied to successions of potential footprints together with other methods for the analysis of the human gait (as, for example, that of Wilkinson et al., 1995). Moreover, the CM becomes precious if associated with other stratigraphical, palaeontological, chemical, archeological and anthropological methods for evaluating the potentially ichnological sites and it also lends itself to pointing out some recent natural and anthropic contaminations and/or alterations of the most ancient traces.

ACKNOWLEDGEMENTS

We are very grateful to Mr. B. F. and Mrs. S.M.Z. for having made possible the experiment on field with their great patience and willingness.

We also thank Mr. Pasquale De Fusco and Mr. Angelo Salvucci for their precious help during the experiment on cement mixture.

We are also very thankful to Maria Rita Palombo, Andrea Sposato and the anonymous reviewer, for their precious comments and suggestions that increased the quality of the manuscript. Finally, we would like to thank Ms Maria Palumbo and Ms Teresa Gray for their linguistic check.

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Ms. received: November 28, 2016
Final text received: June 13, 2017

