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New technologies applied to modelling taphonomic alterations

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A B S T R A C T

Archaeology is developing considerably through the incorporation and application of several methodologies and techniques from science, technology, engineering and mathematics (STEM) disciplines. These technologies have significantly improved our ability to document, preserve, study and present highly precise and accurate digital models of whole sites and archaeological elements, as well as specific details of them. In this article, we will review the different 3D documentation techniques currently available in archaeology, focusing on bone taphonomy. Our aim is to characterise the range of alterations that fossil bones may experience. Thus, here we present a review of the existing literature and future perspectives on how to approach the 3D study of carnivore and rodent tooth marks, cut and percussion marks, biochemical alterations and other Bone Surface Modifications (BSMs).

1. Introduction

A precise and accurate documentation of archaeological sites is paramount for a successful and comprehensive research project. In the surveying stage, having a good representation of the study area (orthophotograph, DTM) can help us better understand the landscape in order to identify traces of human activity (Cowley et al., 2017; O'Driscoll, 2018).

In order to contextualise and document the different elements that the site comprises, there are some documentation geotechnologies (photogrammetry, laser scanning) that are able to digitise places and objects. The resulting models are metrically very accurate, as well as highly detailed and precise. Once the digital data are processed, these models can be visualised in most devices or web servers, obtaining the metric data of the documented element in geometrical, structural, dimensional, and figurative form (González-Aguilera et al., 2009a, b; Torres-Martínez et al., 2016; Carrero-Pazos et al., 2018; Jalandoni et al., 2018; Naranjo et al., 2018). Archaeological remains in particular need to be contextualised within the site (Organista et al., 2017; Siebke et al., 2018), paying particular attention to their shape and geometry for subsequent specific analyses (Yravedra et al., 2017a, b; Hermon et al., 2018).

Lastly, these geotechnologies greatly improve the communication of the results obtained through the use of 3D models. From these models, we can obtain a detailed planimetry, longitudinal and transversal profiles, surface and volume calculations, monitoring object decay or derive orthophotographs, among other options (Cano et al., 2010; García et al., 2011; Cobo et al., 2012; García-Morales et al., 2015; Sabina et al., 2015; Fernández, 2016; Torres-Martínez et al., 2016; Naranjo et al., 2018).

Nowadays, the geotechnologies most frequently used for accurate 3D documentation are: photogrammetric techniques (García et al., 2011; García-Morales et al., 2015; Sabina et al., 2015) and laser techniques (Cano et al., 2010; Cobo et al., 2012; Fernández, 2016). These non-invasive techniques properly complement each other for a high-quality and precise documentation. Originated within the field of Engineering, these techniques are constantly being refined, allowing the establishment of new working methodologies due to technical improvements in fields such as sensor fusion (Torres-Martínez et al., 2016), computer vision (Förstner and Wrobel, 2016), new more robust algorithms, and process automation (González-Aguilera et al., 2016a, b). The application of these technological advancements has significantly contributed to the development of industrial processes (Rodríguez-Martín et al., 2016a, b), architectural planning and cultural heritage (Sánchez-Aparicio et al., 2016, 2018), civil engineering (Zazo et al., 2017, 2018), etc. It is common in disciplines such as archaeology to see these methodologies being adapted to specific research needs, such as the documentation of the different phases of archaeological

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investigation at a site (García et al., 2011; Siebke et al., 2018; Naranjo et al., 2018). It is also worth highlighting the application of photogrammetric techniques to taphonomy, as it has served as the basis of a research methodology based on micro-photogrammetry (M-PG) (Maté-González et al., 2015, 2016, 2017a). This approach has proved capable of achieving results comparable with those obtained using much more costly techniques involving microscopy, (e.g. KH-8700 3D digital microscope (3D DM) and Olympus LEXT OLS3000 laser scanning confocal microscopy (LSCM)) (Maté-González et al., 2017b).

Similarly, terrestrial laser scanner (TLS) soon became an important element in archaeological research, as with other scientific fields and engineering applications (González-Jorge et al., 2012; González-Aguilera et al., 2008, 2009c; Holgado-Barco et al., 2017). In the last few years, TLSs have experienced a radical transformation, from heavy and static with slow data intake and processing to portable hand-held, and more dynamic devices, faster to use and more accurate (Remondino, 2011). The applicability of these sensors is directed to the documentation of objects or nearby landscapes. Most widely-available sensors are based on structured light and/or optical triangulation methods, reaching an accuracy of 0.05-0.02 mm (Remondino, 2011). These devices are also suitable for any kind of workspace and illumination conditions, as they have a built-in software that facilitates data processing. Within archaeology, these systems have been extensively applied to the documentation of rock art, ceramics, fossils, sites, sculptures, jewellery, tombs, etc. (Cano et al., 2010; Komar et al., 2012; Neamtu et al., 2012; Manferdini et al., 2016).

Among the latest advances in the field, a new range of wearable sensors, known as Back-Pack Mobile Mapping Systems (Campos et al., 2018; Lagüela et al., 2018; Masiero et al., 2018), are highly portable and very suitable for the documentation of archaeological landscapes, which would require a rather large number of point-taking stations if they were to be documented using photogrammetry or laser scanning. Nonetheless, they can only reach an accuracy of around 1–3 cm under ideal conditions (Campos et al., 2018; Lagüela et al., 2018; Masiero et al., 2018). These systems may be used instead of airborne Laser Imaging Detection and Ranging (LiDAR) for documenting sites covered under a dense forest canopy, as these devices are able to generate much denser point clouds and they do not require Global Navigation Satellite System (GNSS) (Campos et al., 2018; Lagüela et al., 2018; Masiero et al., 2018).

In the last decade, photogrammetric techniques have experienced a huge development due to the integration of new mathematical algorithms derived from computational vision (e.g. semi-global matching, different global and local detectors and descriptors, multiple matching, etc.), which provide a greater adaptability and flexibility for a wider application of numerical photogrammetric methods (González-Aguilera et al., 2016a, b). Moreover, software and hardware development has consolidated the automation of several processes within the photogrammetric flow (e.g. auto-calibration, dense point cloud model generation, etc.). These advances allow the use of almost any kind of camera while ensuring high quality results (detailed 3D reconstructions and true orthophotographs; González-Aguilera et al., 2016a, b).

As a result of this development, 3D documentation has evolved considerably, from the study of whole single objects or landscapes for the generation of profiles, planes, volumetric calculations, deformations (e.g. a vase, a sculpture, a historic building, a site, etc.) to a more specific and targeted perspective, focusing on particular features of the element under study (e.g. fissures, taphonomic alterations, material deformations, multi-spectral and hyper-spectral analyses, etc.). Following these new lines of research, some authors have developed new methodological advances (Fort et al., 2013; Gajski et al., 2016; Maté-González et al., 2015, 2016; 2017a; Esteve et al., 2018).

The application of laser and photogrammetric techniques combined with statistical analyses have been particularly successful in the field of bone taphonomy (Maté-González et al., 2015, 2016, 2017a, b, c; Aramendi et al., 2017; Arriaza et al., 2017, 2018; Courtenay et al., 2017, 2018, 2019; Palomeque-González et al., 2017; Yravedra et al., 2017a, b, c, 2018). Generally, taphonomic research has relied on microscopic methods for the study of bone surface modifications (BSM) that can be found on fossils (e.g. cut-marks, percussion marks, tooth marks –pits o scores-, biochemical alterations, trampling, etc.), using different techniques, such as optic microscopy, hand lenses and Scanning Electronical Microscope (SEM) and Environmental Scanning Electron Microscope (ESEM) (Shipman, 1981; Olsen, 1988; Greenfield, 1999, 2004, 2006a,b; Smith and Brickley, 2004; Lewis, 2008; Blasco et al., 2016), binocular microscope for high resolution pictures (Domínguez-Rodrigo et al., 2009; De Juana et al., 2010; Marín-Monfort et al., 2014), digital imaging techniques (Gilbert and Richards, 2000), three-dimensional reconstruction (Bartelink et al., 2001; During and Nilsson, 1991; Kaiser and Katterwe, 2001), 3D digital microscope (Boschin and Crezzini, 2012; Crezzini et al., 2014), Alicona 3D Infinite Focus Imaging microscope (Bello and Soligo, 2008; Bello et al., 2009; Bello, 2011; Bonney, 2014), or Laser Scanning Confocal Microscopy (LSCM) (Archer and Braun, 2013).

The combination of microscopic techniques and laser and photogrammetric approaches contributes to a better documentation of the different taphonomic alterations and enables the development of information flows and knowledge transfer between research teams (Maté-González et al., 2017b).

Nowadays, in addition to the aforementioned methods, some authors are developing new techniques involving machine learning and multivariate taphonomic methods for the accurate identification of BSM (Domínguez-Rodrigo, 2018; Domínguez-Rodrigo and Baquedano, 2018). The basis of this work relies on the use of peer expert-identified BSM for the configuration of pre-programmed algorithms, used for the supervised and unsupervised classification of new BSM. The nature of the results obtained highlights the success of these techniques, able to achieve a very high percentage of correct identifications, ratifying the suitability of machine learning approaches for the classification of BSM (Domínguez-Rodrigo, 2018; Domínguez-Rodrigo and Baquedano, 2018).

In the present paper we want to show the usefulness of photogrammetric and laser techniques for the documentation of taphonomic alterations. Therefore, we discuss the results obtained using these techniques when dealing with some of the different taphonomic alterations that may appear in the fossil record, such as cut-marks, percussion marks, tooth-marks, rodent marks and insect alterations. Furthermore, we describe the main features of these alterations for the purposes of a better characterisation and identification. Lastly, we discuss the potential of these techniques to make significant contributions to the discipline of taphonomy, by addressing in the future some of the most pressing debates in the field, such as the nature of the bone surface modifications identified at Dikika or the origin of the Sima de los Huesos bone assemblage.

2. Anthropogenic alterations: cut-marks and percussion marks

Cut-marks and percussion marks on a bone assemblage are direct evidence that humans had access to animal resources, either meat –cut-marks- or marrow –percussion marks-. These traces are very relevant for understanding and interpreting the behaviour of prehistoric populations.

2.1. Cut-marks

Cut-marks are produced when an implement is used to deflesh the bone surface. They are characterised by a V-shaped profile with fine internal striations. Their length varies, and they can have a transversal, oblique or longitudinal orientation. Furthermore, their width and depth vary on the basis of the type of tool, the raw material of the implement, and bone morphology (Martin, 1909; Binford, 1981; Potts and Shipman, 1981; Bunn, 1982, 1983; Shipman, 1981, 1983; Shipman and

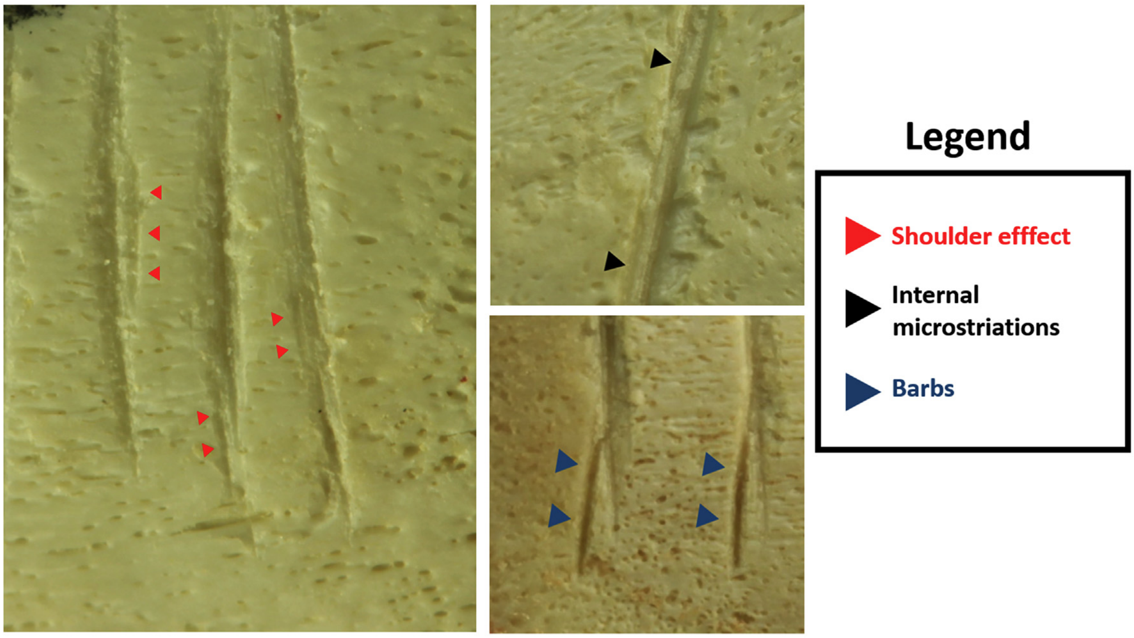

Fig. 1. Characteristic features of cut-marks. In red: *Shoulder effect*; in black: *Microstriations*; and in blue: *Barbs*. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Rose, 1983, 1984; Fisher, 1995; Domínguez-Rodrigo and Yravedra, 2009) (Fig. 1). Cut-marks may show other secondary traces that can help us distinguish them, such as internal micro-striations, barbs, shoulder effects or Hertzian cones (Martin, 1909; Binford, 1981; Potts and Shipman, 1981; Shipman, 1981, 1983; Shipman and Rose, 1983, 1984; Fisher, 1995; Domínguez-Rodrigo and Yravedra, 2009).

The study of cut-marks can be approached from several perspectives:

- The frequency and distribution of the marks can help us distinguish different human behavioural strategies, as highlighted during the hunting vs scavenging debate (Domínguez-Rodrigo et al., 2007, Domínguez-Rodrigo, 1997a, b, c; Lupo and O'Connell, 2002). It can also help us identify systematic exploitation patterns, as documented at Coímbre Cave (López-Cisneros et al., 2018) or to identify the range of activities that were carried out (e.g. defleshing, disarticulation, evisceration, etc.) (Binford, 1981; Lyman, 1987; Nilsen, 2001; Galán and Domínguez-Rodrigo, 2013; Bello et al., 2015).
- The analysis of cut-mark morphology can let us distinguish what kind of implements were used for butchery or what raw materials were selected for manufacturing those tools.

From this last perspective, a number of papers have been recently published, looking at the differences between cut-marks generated with metal knives from those made with stone implements (Olsen, 1988, Greenfield, 1999, 2004, 2006a, b; Bello and Soligo, 2008; Yravedra et al., 2009; Maté-González et al., 2016) (Fig. 2). Others have focused on raw material differences within the same stone tool type, such as flint and quartzite (Palomeque-González et al., 2017; Maté-González et al., 2016, 2017c; Yravedra et al., 2017a, b). Similarly, they have looked at cut-marks generated with different types of stone tools, such as unmodified flakes, retouched flakes, or bifaces (Fig. 3) (Walker, 1978; Shipman and Rose, 1983; Bello et al., 2009; Domínguez-Rodrigo et al., 2009; De Juana et al., 2010; Galán and Domínguez-Rodrigo, 2013; Courtenay et al., 2017). Lastly, it is also worth mentioning the studies focusing on raw material granulometry which aimed to understand how it might affect cut-mark morphology (Dewbury and Russell, 2007; Moclán Ramos, 2016; Maté-González et al., 2017c; Courtenay et al., 2017).

2.2. Percussion marks

Percussion-marks are generated in the process of breaking the bone to access the marrow cavity or as part of the carcass disarticulation process. They have a rounded or oval shape, broadly similar to tooth-marks, but they show internal microstriations and an irregular bottom (Bonnichsen, 1979; Binford, 1981; Johnson, 1983, 1985; Blumenschine and Selvaggio, 1988; Blasco-Sancho, 1992; Lyman, 1994).

Percussion marks can be generated using either unmodified or modified hammerstones. The traces left by modified hammerstones are more readily identifiable: they are more oval in shape, have clear internal striations and an irregular bottom (Galán et al., 2009; Blumenschine, 1995). On the other hand, percussion marks generated by unmodified hammerstones can sometimes be misinterpreted as pits (Blumenschine, 1995, p495). Nonetheless, with the aid of a photogrammetric or laser documentation (Maté-González et al., 2015, 2016, 2017a, b), alongside geometric morphometric analyses, percussion marks generated by unmodified hammerstones can be distinguished from carnivore tooth marks (Yravedra et al., 2018). In Fig. 3 we can see the difference between the percussion marks generated by unmodified and modified hammerstones.

3. Biological alteration processes

3.1. Carnivores

Carnivores can produce different types of marks with their teeth. For some authors (Haynes, 1983; Solomon and David, 1990), each tooth shows a particular alteration pattern: incisors would produce scores, whereas canines and molars would produce pits. Pits and scores are the most frequent types of tooth marks and are the ones we discuss here, although there are other marks, such as rewaging (Binford, 1981), chipping (Martin, 1907-10, Blasco-Sancho, 1992), or groves (Blumenschine and Selvaggio, 1988; Fisher, 1995), among others.

3.1.1. Scores

Scores are elongated, wide and sinuous tooth-marks, with U-shaped section, flat bottom and rounded edges. They vary notably in terms of length, although they are generally three times longer than their width.

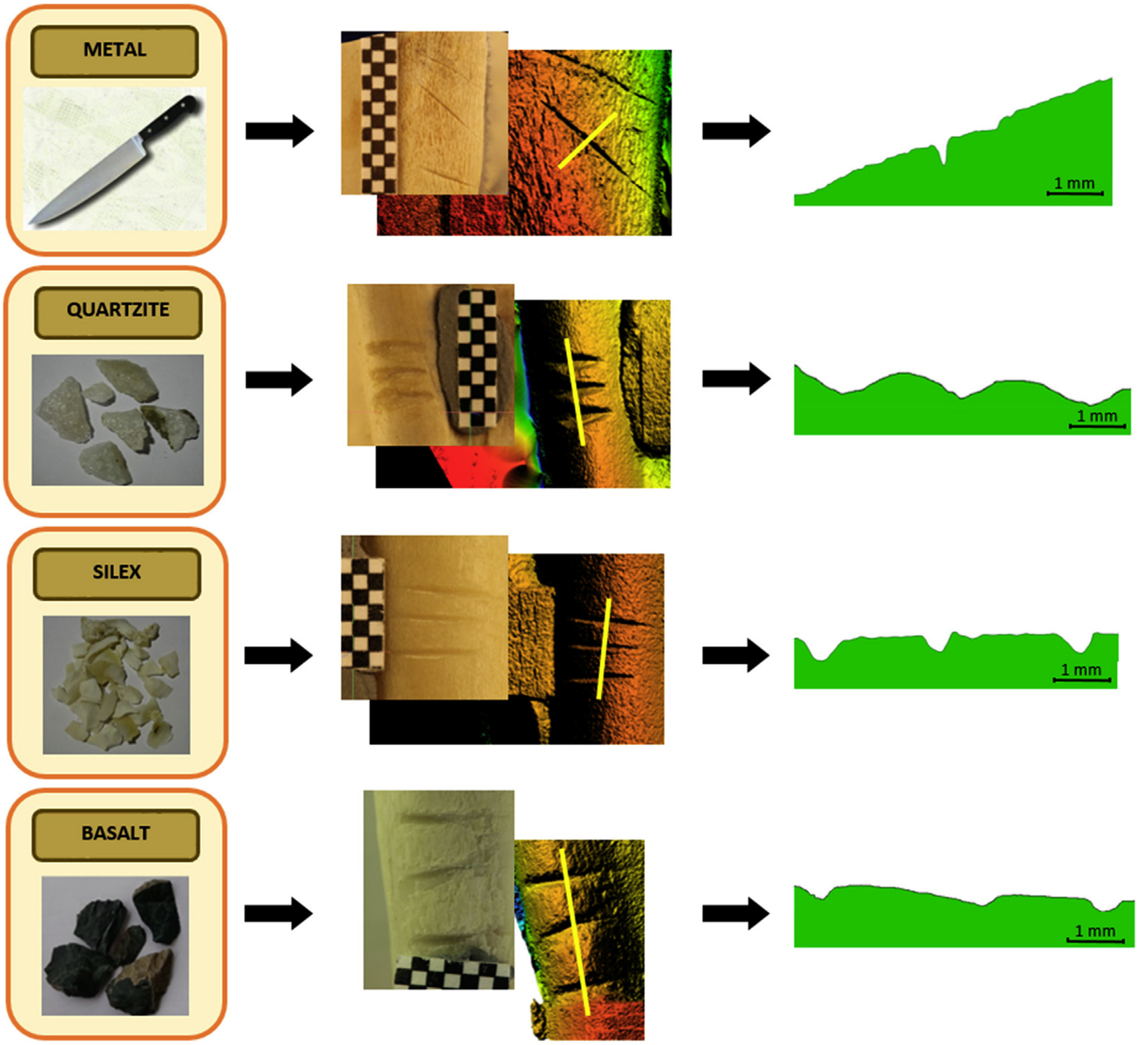

Fig. 2. Cut marks generated with: a metal knife, a quartzite flake, a basalt flake and a flint flake. Detail for the V sections of each mark. The models shown in the present figure were generated using micro-photogrammetric techniques.

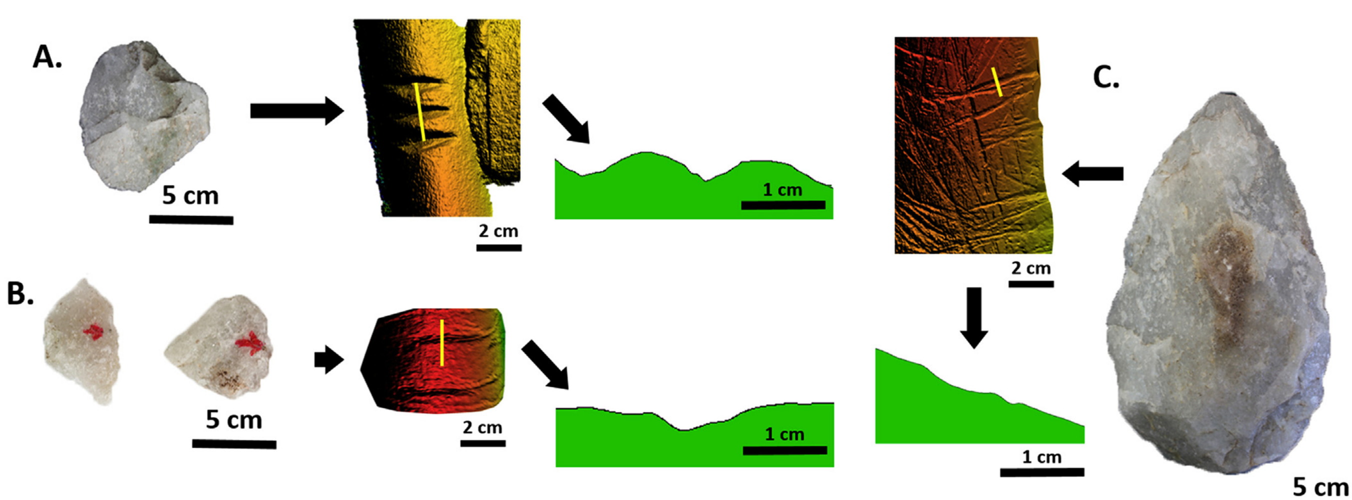

Fig. 3. A. Unmodified quartzite flake. B. Retouched quartzite flake. C. Quartzite biface. In detail: for the V-sections of each mark, respectively. The simple flake (A) has a narrower and deeper section than both the retouched flake (B) and the biface (C.). The retouched flake (B) therefore has a more open and superficial section than the simple flake (A), whereas the biface (C) has a more open and superficial section than the retouched flake (B). The models shown in the present figure were generated using micro-photogrammetric techniques.

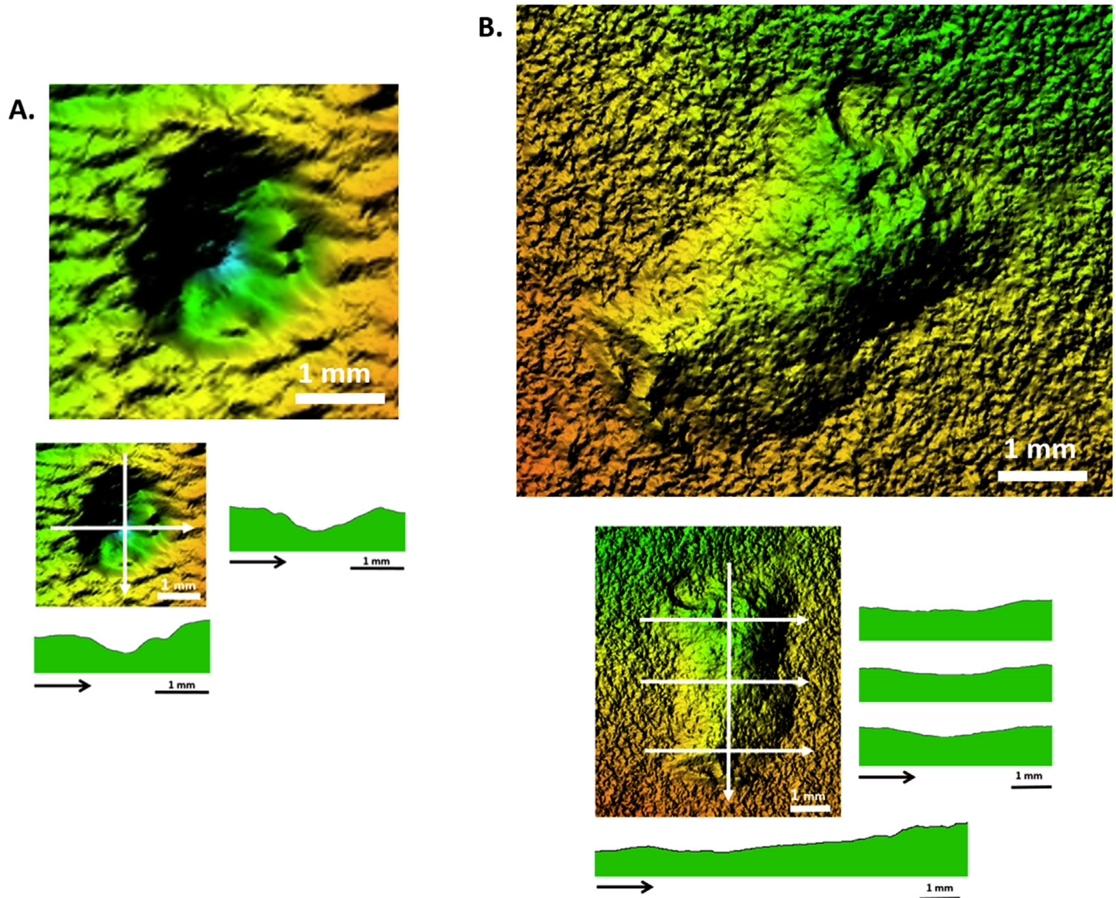

Fig. 4. A. Unmodified hammerstone (circular shape). B. Modified hammerstone (oval shape). We can see in the 2D profiles the internal striations and the irregular bottom shape. The models shown in the present figure were generated using laser techniques.

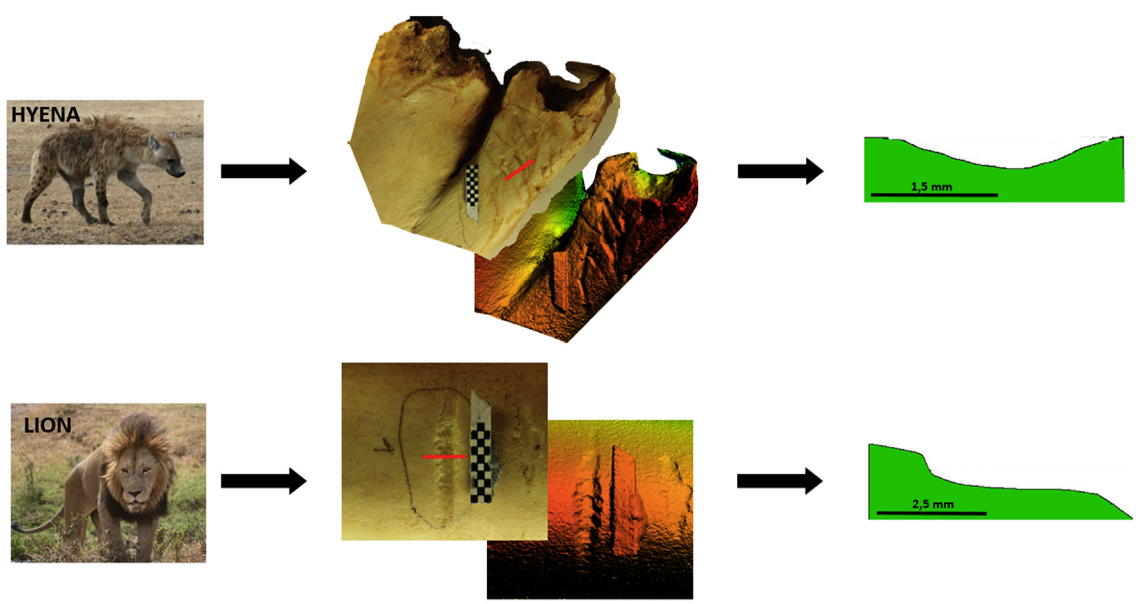

Fig. 5. Scores produced by a spotted hyena and a lion. The detail shows the characteristic U-shaped section of scores. The models shown in the present figure were generated using micro-photogrammetric techniques.

Scores preferentially show a transversal orientation (Bunn, 1981; Binford, 1981; Shipman, 1983; Eickhoff and Herrmann, 1985; Reixach, 1986; Solomon and David, 1990; Blasco-Sancho, 1992; Martínez Moreno, 1993; Blumenschine et al., 1996). They are generally produced when a carnivore drags its incisors along the bone surface. Scores do not cause cortical collapse and they are associated with circular and uniform depressions. They do not become narrower on the edges, unlike cut-marks (Haynes, 1983; Solomon and David, 1990) (Fig. 5).

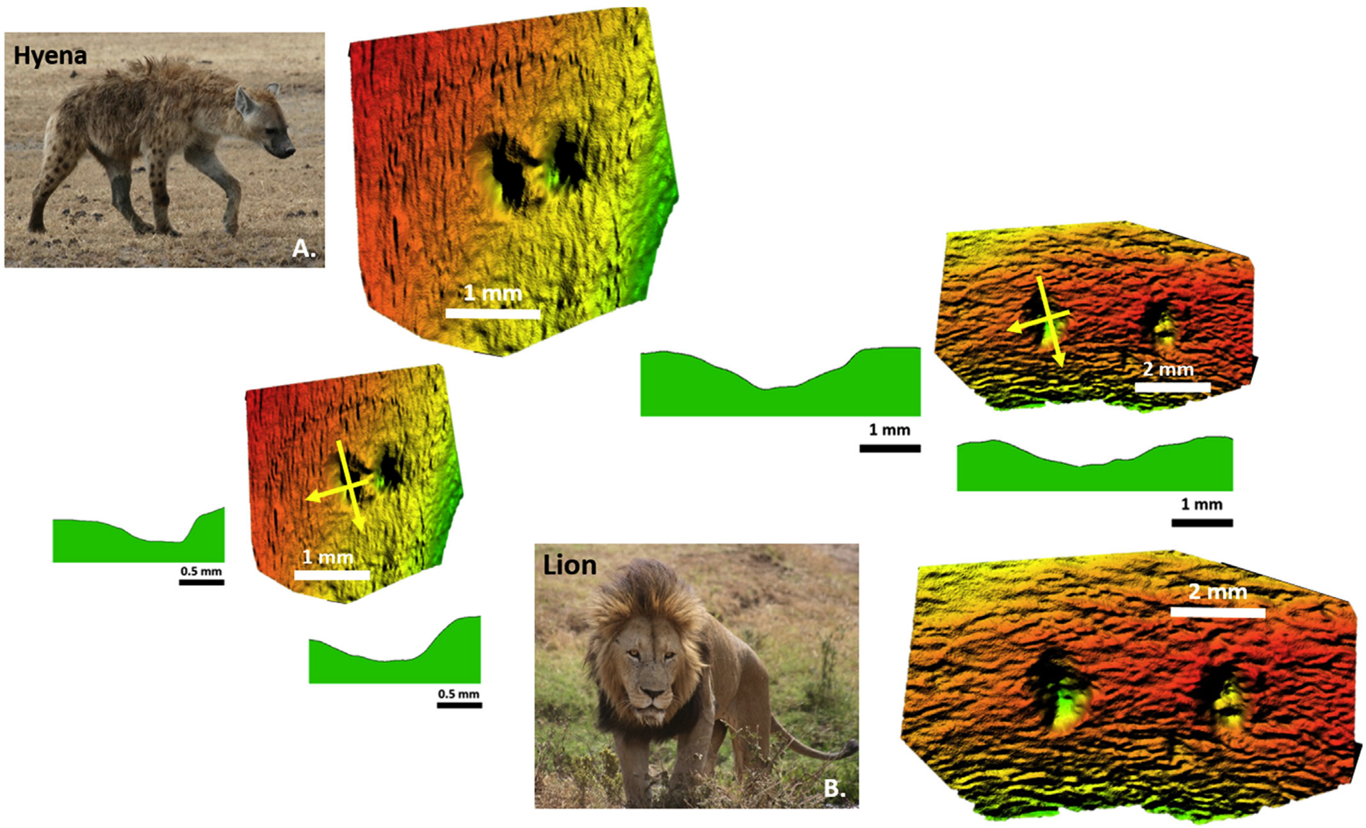

Fig. 6. Showing pits generated by a hyena and a lion. Note the flat bottom of the profiles. The models shown in the present figure were generated using laser techniques.

3.1.2. Pits

Pits are shallow, circular-shaped marks, with flat bottom and rounded edges. They are usually associated with the action of biting with the canines or molars (Fig. 6) (Binford, 1981; Haynes, 1983; Johnson, 1985; Reixach, 1986; Blasco-Sancho, 1992; Arriaza et al., 2018). As mentioned above, they share similar attributes to percussion marks made with unmodified hammerstones (Pickering and Egeland, 2006; Galán et al., 2009; De Juana and Domínguez-Rodrigo, 2011); however, the application of new methodological approaches has improved our ability to correctly identify between these two types of marks (Yravedra et al., 2018).

3.2. Rodents

Not only carnivores generate tooth-marks; other agents, such as rodents, are also capable of producing them. Rodent marks are small, deep parallel incisions, symmetrical and with a wide and flat bottom. They tend to appear on bone ends or edges (Weigelt, 1989; Pei, 1938; Bouchud, 1974, Brain et al., 1980; Maguire et al., 1980; Brain, 1981). The bones usually targeted by rodents are cranial, mandibular and axial elements, as well as epiphyses of long bones (Brain, 1981).

Rodent marks follow a fan-shaped pattern characterised by a range of parallel striations with rugged and parallel edges (Pei, 1938) (Fig. 7).

3.3. Insects

Insects can cause alterations on the bone surfaces. These traces were first studied by Smith (1908), Derry (1911), Weigelt (1989) and Piepenbrink (1986). Insects produce small perforations with a flat edge (Andrews, 1995), which may poke through the bone surface (Fig. 8). Many authors have described the actions of beetles (Dupuy de Lome and Fernandez De Caleya, 1918; Weigelt, 1989; Payne, 1965; Hefti et al., 1980), ants (Behrensmeyer, 1978), larvae (Shipman and Walker, 1980) or termites (Watson and Abbey, 1986).

4. Discussion

Alongside the processes discussed above, there are other agents that may alter fossil bone assemblages, such as birds (Dodson and Wexlar, 1979; Andrews, 1983, 1990), herbivores (Sutcliffe, 1973; Brothwell, 1976; Cáceres, 2002), omnivores such as pigs (Domínguez-Solera and Domínguez-Rodrigo, 2009), bacteria and other microorganisms (Miller, 1994; Hackett, 1981; Garland, 1987, 1988), etc. All of them may be reconstructed as 3D models for further statistical and morphometrical analyses, as shown in Figs. 1–6.

The use of photogrammetry and laser techniques allows us to undertake a detailed study of any taphonomic alterations that we may find in the archaeological record. The resolution is sufficiently precise as to match the results of almost unreachably costly equipment (3D DM and LSCM) (Maté-González et al., 2017b).

By themselves, these techniques grant us a global understanding of the morphometry of these taphonomic alterations; however, when we combine them with geometric morphometrics and multivariate statistics, they become a powerful analytical device for a comprehensive study of identification and characterisation of BSM (Maté-González et al., 2015, 2016, 2017a, b, c; Aramendi et al., 2017; Arriaza et al., 2017, 2018; Courtenay et al., 2017, 2018; Palomeque-González et al., 2017; Yravedra et al., 2017a, b, c, 2018).

Thus, at the site of BK (Bell's Korongo – Upper Bed II) (Garganta de Olduvai, Tanzania) (Yravedra et al., 2017a) butchery processes are associated with a particular raw material: an analysis of this nature identified that 81% of the cut-marks from the site of BK were made using quartzite implements. This result is in agreement with previous studies, which suggested that quartzite were the predominant raw

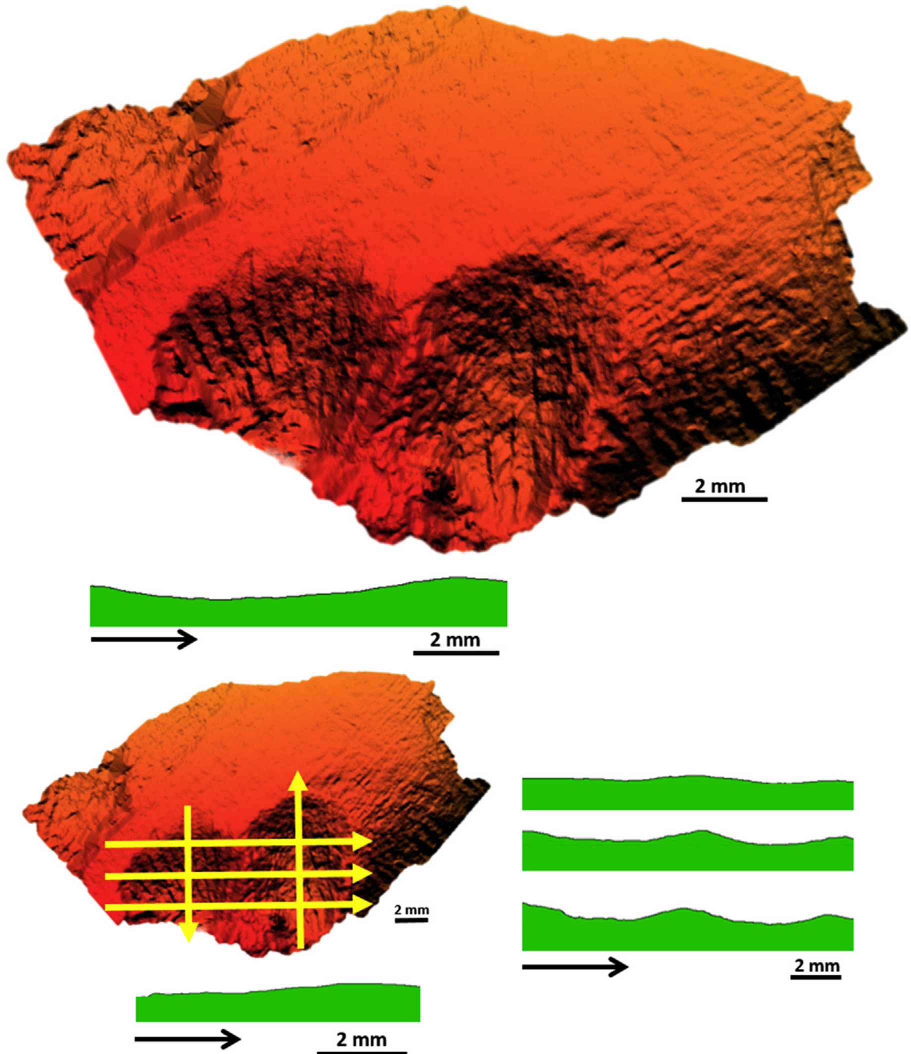

Fig. 7. Bone with rodent marks. Note the characteristic fan-shaped pattern caused by the parallel striations with rugged edges in both the image and the detailed profiles. The models shown in the present figure were generated using laser techniques.

material for butchery implements at the site (Leakey, 1971, Kyara, 1999, Díez et al., 1999a, b).

These researchers have also shown through photogrammetric and geometric morphometric analyses that the cut-marks at the site of FLK West (Frida Leakey Korongo) (Garganta de Olduvai, Tanzania), were made with quartzite flakes rather than handaxes (Yravedra et al., 2017b). Thus, handaxes at this site were not used for butchering animal carcasses; instead, they may have had other purposes, such as the exploitation of plant resources.

Perhaps an analysis of this kind could elucidate the nature of the marks identified at the site of Dikika, i.e. whether they are cut-marks (McPherron et al., 2011; Thompson et al., 2015) or not (Domínguez-Rodrigo et al., 2010, 2011, 2012).

The study of hominin-carnivore interactions is of great relevance for understanding our evolutionary record. Carnivores do not only alter skeletal profile, but their action can also erase and/or mimic the traces made by other agents, such as humans (Maltby, 1985; Grayson et al., 1988). Therefore, it is paramount to properly characterise carnivore alterations to not misidentify them as percussion marks (Yravedra et al., 2018), to avoid attributing to human agency the action of carnivores.

With regards to carnivore alterations, laser and photogrammetric techniques have also been successfully applied to different case-studies (Aramendi et al., 2017; Arriaza et al., 2017, 2018; Yravedra et al., 2017c). Looking at scores and pits, these techniques have contributed to demonstrating the hypothesis derived from previous taphonomic research that first lions and then hyenas altered the bone assemblage found at Olduvai Carnivore Site (OCS) (Arriaza et al., 2017, 2018).

When applied to pits, these techniques have been able to demonstrate the hypothesis suggested by Baquedano et al. (2012). The analysis of the pits found on two *Homo habilis* specimens (OH8 and OH35) from Olduvai Gorge indicate that OH8 have crocodile-inflicted tooth-marks, whereas the tooth-marks found on OH35 were caused by a different kind of carnivore (e.g. hyena, lion, jaguar, jackal) rather than crocodiles (Aramendi et al., 2017).

These analyses are particularly useful for understanding the archaeological record of Pleistocene sites. This is true for sites from Olduvai Gorge Beds I and II, because these techniques can help distinguish the actions of lions and hyenas, both of which may have played a part in the modification of bone assemblages (Domínguez-Rodrigo et al., 2007; Arriaza et al., 2016).

At the same time, there are other sites for which these techniques may prove useful, such as the Middle Pleistocene site of Sima de los Huesos (Atapuerca, Spain). Andrews and Fernández-Jalvo (1997) argue that lions ate the human remains found at the site, whereas Arsuaga et al. (1997) and Sala et al. (2014) argue that it was an anthropogenic-accumulated assemblage which was later altered by bears. A morphometric analysis of the remains could help determine if felid-induced tooth-mark damage could be found on the hominin skeletons.

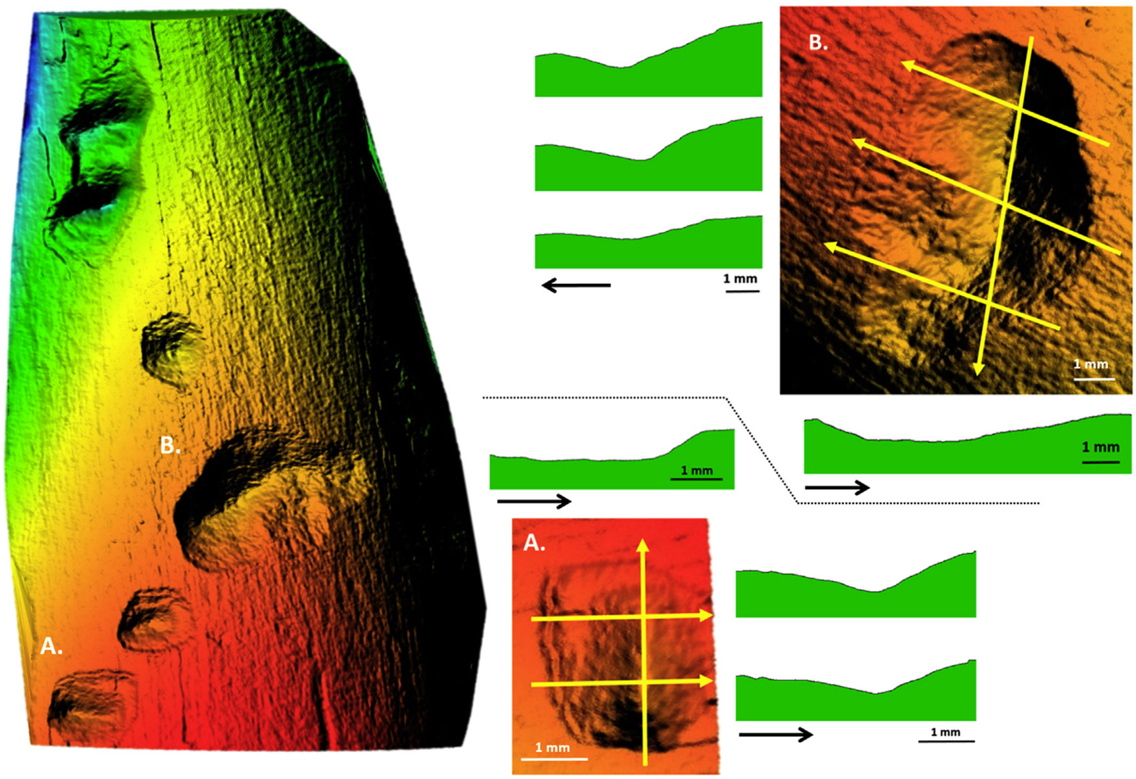

Fig. 8. Bones with insect marks. A three-dimensional analysis shows deep marks with a U-shaped transversal section, with a flat longitudinal section. As these marks may be irregular and flaky, different heights might be noted inside them. The models shown in the present figure were generated using laser techniques.

As we have discussed, the techniques proposed in the present paper afford a new way of documenting and analysing taphonomic alterations. They offer high-resolution 3D models, with short processing times and affordable pricing for the broader scientific community (Maté-González et al., 2015, 2016, 2017a, b). Thus, it offers a new methodological approach for the taphonomic study of complex and problematic sites.

At the same time, there are some slight disadvantages of using this method. Micro-photogrammetric techniques (passive sensor) require a larger volume of captured data and more processing time than microscopic and laser technique (active sensor), as well as some photogrammetric experience for the adequate fulfilment of the different technical phases, such as data-gathering protocols or device calibration and orientation (Maté-González et al., 2015, 2016, 2017a). Furthermore, even though they are quire efficient, they still do not match the resolution of some microscopes with regards to the documentation of more superficial BSM, such as trampling (Maté-González et al., 2015, 2016, 2017a, b). However, we argue that their advantages, namely that they are very affordable, accessible for the wider scientific community, easily portable for working at sites and museums, outweigh these disadvantages in most scenarios (Maté-González et al., 2015, 2016, 2017a, b).

Meanwhile, other authors have developed other alternative documentation systems of taphonomic alterations form 3D models (Pante et al., 2017; Ortorola-Castillo et al., 2018) or have criticised the results obtained in the last few years within the field of taphonomy (Sahle et al. (2017)).

Sahle et al. (2017)'s critique of taphonomic research conducted during the last 30 years has been rightly criticised by Domínguez-Rodrigo and Baquedano (2018) who have demonstrated that Sahle et al. (2017)'s subjective view lacks any empirical support.

Pante et al. (2017) introduced a system called white-light noncontact confocal profilometers using Digital Surf's Mountains R software. In order to demonstrate its viability, they undertook a comparative study to distinguish between stone tool cut marks and mammalian carnivore tooth marks. With this method, Pante et al. (2017) achieved very high levels of success (near 100%).

On the other hand, Otárola-Castillo et al. (2018) developed another system known as full 3D morphometrics aided by Bayesian analysis. With this system, they were able to successfully differentiate between experimental cut-marks made on different angles (45° and 90°).

Nevertheless, these studies have several issues. The focus of Pante et al. (2017) i.e. differentiating between cut-marks and tooth-marks, was already amply demonstrated by several authors macroscopically during the 90s, without the need to use those costly and sophisticated technologies (Binford, 1981, Shipman, 1981; Blumenschine & Selvagio 1988; Blumenschine, 1995; Blumenschine et al., 1996; Galán et al., 2009, etc.). Similarly, the study by Otárola-Castillo et al. (2018), consisting on the differentiation between cut-marks made with different angles, can also be easily solved macroscopically. Furthermore, photogrammetric and morphometric approaches combined with multivariate statistics offer an even greater degree of resolution for this task (Courtenay et al. (2018)). Therefore, both of these studies are going to have success a priori with very predictable results, so they do not offer any significant contribution to the field of taphonomy. At the same time, both authors use samples that are not statistically representative, thus casting doubts on the reliability of the analyses (Courtenay et al., 2018). Besides, the techniques applied by Pante et al. (2017) and Ortorola-Castillo et al., (2018), in addition to their relative lack of resolution compared to photogrammetric and geometric morphometric approaches, they are costly and technologically unavailable for most researchers. Similarly, they have the added issue that they have not been tested for accuracy and precision in relation to other techniques and approaches; photogrammetric and laser techniques have been successfully compared to 3DM and LSCM (Maté-González et al., 2017a, b).

5. Conclusions

The combination of these well-tested 3D documentation techniques (3D DM, LSCM, M-PG and SLS) alongside geometric morphometrics, multivariate statistics and machine learning are significantly improving the reliability of taphonomic analyses. Thus, the discipline is now well-equipped to address hotly-debated issues, such as those surrounding the sites of Dikika or Sima de los Huesos.

These analyses present many advantages if applied appropriately, although some these new approaches may come across as redundant otherwise (cf. Pante et al. (2017) or Otárola-Castillo et al. (2018)). Therefore, the best strategy to follow when conducting a taphonomic analysis is two-fold: first, we should consider whether the research question is relevant or futile experimentation. Secondly, once a suitable question has been found, all the potential approaches ought to be considered, selecting the most fitting one, both in terms of accuracy required and resources available, in order to ensure the best possible outcome.

The coming years will bring more technological advances, with the development of powerful hardware and software, even more refined microscopy, new and improved mathematical algorithms, within a more robust statistical framework. The future relevance of taphonomy will rely significantly on their appropriate application.

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Appendix A. Supplementary data

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