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Residual energy dispersal fracturing: A newly proposed term for fractures propagating from sharp-force trauma

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Abstract

Objectives: The identification and interpretation of skeletal trauma is an important topic in osteoarchaeology, forensic anthropology and palaeosciences. Trauma analysis is a fast-moving sub-discipline with constantly evolving methodological approaches. This paper describes the process of a particular form of fracturing that propagates specifically from the floor of cut marks and proposes new terminology for this subset of fractures.

Materials and Methods: This terminological gap was identified during the re-examination of remains from a minimum of 52 decapitated individuals (52 post-cranial and 47 cranial remains) found in a mass grave from the 10th–11th century CE on Ridgeway Hill near Weymouth in Dorset (UK) in 2009. Originally analyzed by Oxford Archaeology Ltd., all individuals in this collection were re-appraised using digital technology to test new techniques for this study.

Results: During this investigation, it has become apparent that the length of chop marks can be overestimated during some conventional analysis because the chop transitions into a fracture propagating from the floor of the chop mark.

Discussion: To increase awareness of these fractures, the term residual energy dispersal (RED) fractures is proposed as these are distinct from other radiating fractures arising from sharp-blunt-force trauma. The ability to distinguish RED fractures from others has the potential to contribute to the identification of previously unidentified chop marks and to the interpretation of events surrounding an injury.

KEYWORDS
biological anthropology, fracturing, osteoarchaeology, sharp-force trauma, trauma analysis

1 | INTRODUCTION

The analysis of trauma is an important aspect of osteoarchaeology, forensic anthropology and other palaeosciences. In the former, it helps reveal more information about past events, societies, intra- and inter- personal violence and in the latter, it is an integral aspect of trying to ascertain what may have happened to an individual (Cunha & Pinheiro, 2016; L'Abbé et al., 2019; Lovell, 1997; Roberts, 2000; Ubelaker & Montaperto, 2013). Within the field of trauma analysis, the terms "radiating fracture" or "secondary fracture" is commonly

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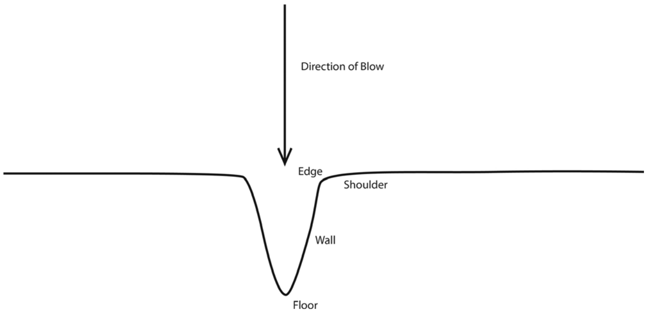

FIGURE 1 A diagrammatic profile of a chop mark, caused by sharp-force trauma

applied to additional indirect fractures to bone associated with blunt-force trauma and projectile trauma. These fractures are found either traveling toward or away from the point of impact, depending on the bone affected, the location on the bone, and the nature of the force exerted (Isa et al., 2019). Fractures propagating from chop marks, however, are less frequently discussed.

This article sets out to investigate the causative relationships between sharp-force damage to bone and a specific form of fracturing that can occur as a result. We propose a new recording term to help distinguish fractures propagating from sharp-force trauma, from fractures of other etiologies, such as post-mortem breakage. Additionally, the differentiation and delineation between chop marks and resultant fracturing could add to knowledge of how such injuries occurred and help identify other potential chop marks. It draws on the results of a case study of 52 decapitated individuals (cranial Most Likely Number of Individuals [MLNI] = 47, post-cranial MLNI = 52) from a 10th-11th century mass grave in Dorset. These remains have significant amounts of peri-mortem chop marks and associated fractures (Loe et al., 2014).

1.1 | Background

1.1.1 | Trauma

Trauma occurs when an external force acts upon the body and results in damage to living tissue, specifically when that force is greater than the bone can withstand, leading to structural failure (Cunha & Pinheiro, 2016; L'Abbé et al., 2022; Lovell, 1997; Roberts, 2000; Symes et al., 2012). There are multiple categories of osseous trauma that relate to the shape and magnitude of the causative force, each resulting in different characteristic wound patterns; sharp-force trauma (SFT, Figure 1), blunt-force trauma (BFT) and projectile/ballistic trauma (PT). All of these can result in fracturing of the bone. Fracturing associated with SFT is often classified as the hybrid sharp-blunt-force trauma (SBFT), which is also sometimes known as chopping or hacking trauma (Alunni-Perret et al., 2005, 2010; Nicklisch et al., 2017). This occurs when a heavy bladed object strikes a bone, leaving a chop mark (SFT component) as well as fracturing around the site (BFT component) (Alunni-Perret et al., 2005; Downing & Fibiger, 2017; Loe, 2016; Nicklisch et al., 2017). This article uses "chop marks" to differentiate this type of SFT from "cut marks", which are typically smaller and finer, with a V-shaped profile (Loe et al., 2014).

TABLE 1 The different morphological traits seen in peri- and post-mortem fractures

Morphological trait	Peri-mortem	Post-mortem
Plastic deformation	Yes	No
Staining of the bone fracture surface (patination)	Similar to bone surface	Different in color than bone surface
Fracture surface	Clean and smooth	Jagged/stepped edges
Fracture angle	Obtuse/acute	Right
Fracture outline	Concentric and radiating	Perpendicular or horizontal
Fracture margins	Peeling or lifting	Rough and uneven
Loading point	Yes	No
Area adjacent to the fracture site	Small bone fragments adhere to site of fracture	Often break into multiple pieces

Note: Adapted from Łukasik et al., 2019 Table 2, p. 285. Ubelaker & Montaperto, 2013; Galloway et al., 2014; L'Abbé et al., 2019, 2022.

The timing of an injury is an important aspect of trauma analysis (Coelho & Cardoso, 2013; Sauer, 1998). Clinical medicine, pathology, forensic anthropology, and osteoarchaeology commonly use three terms regarding the timing of an injury compared to the time of death: ante-, peri-, and post-mortem (before death/healed, around the time of death/biomechanically fresh or wet bone, and after death/dry bone) (Boylston, 2000; Fleischmann, 2019; Galloway et al., 1999; L'Abbé et al., 2015; 2019; 2022; Symes et al., 2012). Ante-mortem trauma occurs prior to death and is evidenced by signs of at least short-term survival after injury, such as remodeling, infection, or necrosis. However, more importantly for this study is the differentiation of peri-mortem and post-mortem fracturing. This is challenging as although there is general agreement that bones retain properties of vital fracturing, for a period after death, the length of this period and the variables (i.e. depositional context) that influence remain difficult to predict. (Cappella et al., 2014; Cohen et al., 2012; L'Abbé et al., 2019). Peri-mortem trauma is considered to have taken place around the time of death, whilst the bone maintains its living properties (wet, green, or biomechanically fresh bone) but not long enough before death for any healing to have occurred. Post-mortem damage, often being measured in centuries or even millennia in osteoarchaeology, occurs after death and becomes discernible anthropologically after the loss of the organic components of the bone, which causes bone to fracture in rough, irregular patterns since the bone is more brittle and less elastic (dry bone) (Cohen et al., 2012; Cunha & Pinheiro, 2016; Fleischmann, 2019; Galloway et al., 1999; L'Abbé et al., 2015, 2022; Lovell, 1997; Łukasik et al., 2019; Nawrocki, 2016; Sauer, 1998; Wheatley, 2008). This category can be further sub-

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TABLE 2 The differences in force, velocity, and appearance in different types of trauma

Trauma	Velocity	Force	Size and shape
Blunt-force Trauma	Moderate	Moderate	Associated with weapon
Sharp-force Trauma (SFT)	Moderate	Moderate to high	Thin Linear
Projectile/ballistic trauma (PT)	High	High	Small Concentrated

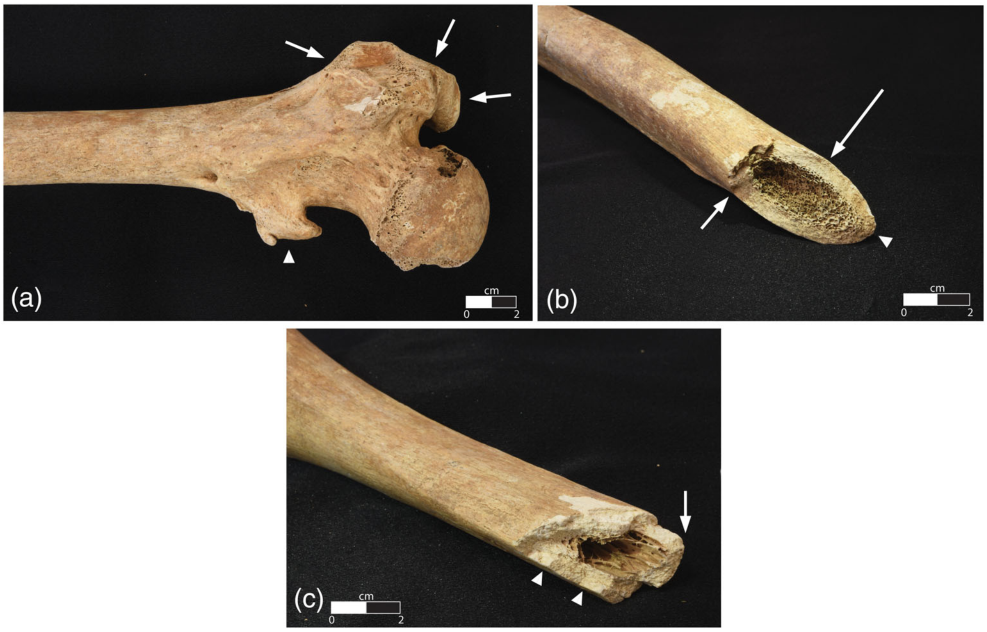

FIGURE 2 Images of fractures: (a) healed ante-mortem fracture of a right femur displaying remodeled bone around the greater trochanter (white arrows) and evidence of associated muscle trauma at the attachment for the iliopsoas (white arrowhead), (b) peri-mortem fracture of a left femoral shaft displaying characteristic patinated fracture surfaces (long white arrow), a helical or spiral outline ending in a point rather than a transverse surface (white arrowhead), and arrest ridges and a cantilever curl which both indicate impact location (white arrow; Christensen & Hatch, 2019), and (c) post-mortem fracturing of a left tibia shaft exhibiting transverse, stepped edges (white arrowheads) and fracture surfaces that are much lighter than the surrounding bone (white arrow)

divided into mineralized breaks (minimal or no collagen remaining) and dry fractures (occurring after death but before the complete loss of collagen) (Crozier, 2018; Knüsel & Outram, 2012). The differences in appearance of peri- and post-mortem fractures are summarized in Table 1, with examples of each type in Figure 2.

1.1.2 | The mechanics of fracturing

Fracture properties of materials have been well documented for over three centuries and aspects such as the geometry of the structure, the mechanical properties of the materials, and the location, direction, and magnitude of the loads are all critical factors in understanding fracturing (Christensen & Hatch, 2019; Gauthier, 2017; Hayes et al., 1991; Kieser et al., 2013; L'Abbé et al., 2022; Lawn, 1993; Timoshenko, 1983). Although there are multiple methods of fracture initiation, the one under investigation here is Mode I, when the material is split apart with the crack initiating from the same side and location as the external force (Figure 3) (Kieser et al., 2013; Lawn, 1993). Two important principles will be highlighted briefly before the focus will move to fracturing of bone specifically.

The stress applied to an object is affected by the magnitude of the loading force and the area that it is applied over $\left(\sigma = \frac{F}{a}\right)$ (σ: stress [N/m^2], F: force [N], a: area [m^2], Kieser et al., 2013). Strain is the change in the shape of an object through loading divided by the dimension before the loading $\left(\varepsilon = \frac{\Delta l}{l}\right)$ (ε: strain [no unit], Δl: change in length [m], l: original length [m], Kieser et al., 2013). The relationship between stress and strain is determined by the material in question and the ratio of stress to strain is known as Young's modulus (Figure 4) (Kieser et al., 2013; L'Abbé et al., 2022).

Fracturing in bone

The risk of a bone fracturing can be defined as the ratio of the applied load to the bone strength (Hayes et al., 1991). The biomechanics of living bone and the manner in which it fractures is significantly influenced by its organic component. It is considered a visco-elastic

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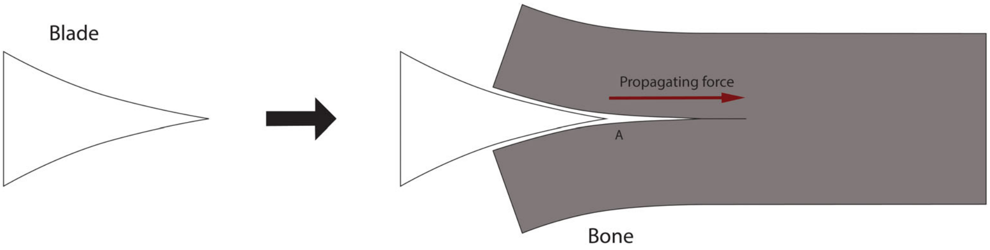

FIGURE 3 Diagrammatic representation of how a blade could cause fractures propagating from the floor of the chop mark. The area of bone to the right of point A is not contacted by the blade but is instead delaminating at a microstructural level as kinetic energy is imparted

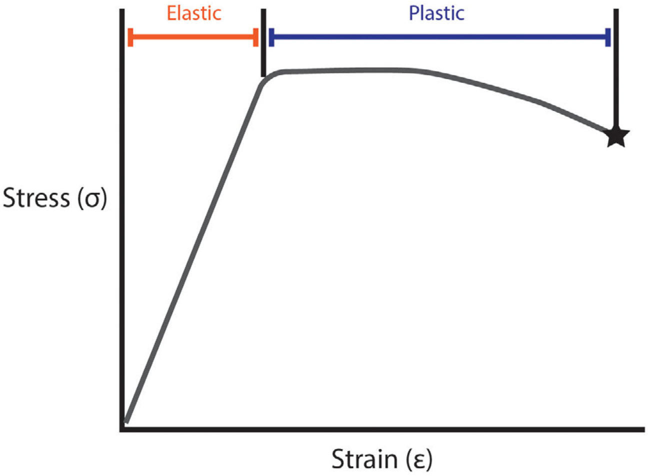

FIGURE 4 A stress–strain graph of bone showing how Young's modulus can be plotted to visualize the increase through an elastic zone (non-permanent deformation) to a plastic zone (permanent deformation) until eventual failure (amended from Kieser et al., 2013, Figure 2.4, p. 15)

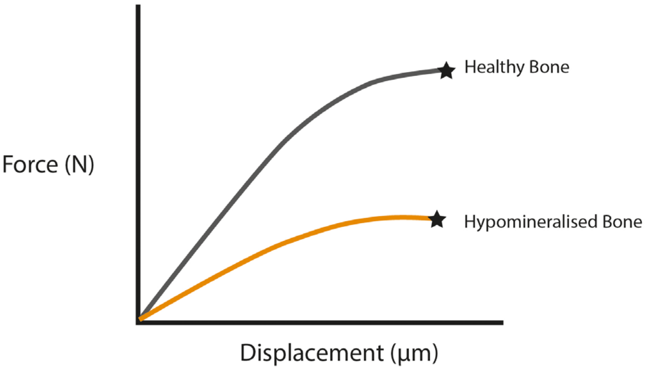

FIGURE 5 An example of how hypomineralised (dry) bone effects the force required to cause deformation (amended from Kieser et al., 2013, Figure 3.2, p. 40)

material, which has a fracture process that is not as straightforward or well understood as brittle or elastic materials. The organic components of living bone (mainly Type I collagen) provide tensile strength and inorganic components (hydroxyapatite crystals $Ca_{10}(PO_4)_6(OH)_2$) add compressive strength to the bone (Kieser et al., 2013; Loe, 2016; Pechníková et al., 2011; Sauer, 1998; Symes et al., 2012). Bone also contains moisture, fats, and vasculature, which further determine the reaction of bone to external forces (Nawrocki, 2016).

Since the composition of a material influences fracture mechanics, the differences between the composition of living and dried bone, especially the loss of organic material, directly influence the appearance of fracturing (Hayes et al., 1991). More elastic living bone will take longer to move into the plastic stage where deformation become permanent, creating peri- mortem fractures, whereas the more brittle dry bone has a very limited elastic phase resulting in the characteristics seen with post-mortem fracturing (Figure 5).

Bone is classified as anisotropic because it is organized longitudinally, such that mechanical properties are different along the diaphyseal axis compared to transverse (Loe, 2016; Symes et al., 2012). Following Wolff's Law, bone adapts to the loading forces and different stresses and strains that are put upon it over time, and both the macroscopic and microscopic architecture of the bone can slow, redirect, or arrest fracturing (Kieser et al., 2013; Ruff et al., 2006; Voide et al., 2009).

Fractures will propagate through bone away from the initiation point until the energy has entirely dispersed (Galloway et al., 1999). Generally, the force follows the path of least resistance, avoiding the thicker, buttressed areas of bone and traveling through the thinner areas, often toward fossae or foramina (Berryman & Jones Haun, 1996; Berryman & Symes, 1998; Cohen et al., 2012). At natural points, junctions, or points of weakness, fractures will often change direction or dissipate if it encounters a discontinuity (e.g., fractures, cranial sutures) (Berryman & Symes, 1998; Loe, 2016; Lovell, 1997; Nicklisch et al., 2017).

There is extensive literature relating to bone biomechanics and force propagation (e.g. Bonfield & Datta, 1976; Kieser et al., 2013; L'Abbé et al., 2022; Pope & Outwater, 1972). Intrinsic factors such as the organic component, the bone mineral density, the hierarchical organization of the bone structure, the capacity of the bone to absorb energy, the size and shape of the bone, and health status affect bone fracturing (Bartelink, 2015; L'Abbé et al., 2022; Martin & Harrod, 2015; Ubelaker & Montaperto, 2013; Voide et al., 2009; Wheatley, 2008). More importantly within this article are the extrinsic factors, such as external load on the bone, the velocity, duration, speed and force of a strike, and the size and shape of any external objects impacting the bone, because this will differentiate the appearance of SFT, BFT, and PT (Table 2) (Bartelink, 2015; Berryman & Jones Haun, 1996; L'Abbé et al., 2022; Lovell, 1997; Martin & Harrod, 2015; Ubelaker & Montaperto, 2013).

Li et al. (2013) found that it took a lower force to initiate fractures along the longitudinal axis of the osteons compared to the transverse axis. This supports the findings that microscopic cracks usually follow the cement lines that run longitudinally where osteons meet as this is a weaker interface (Kieser et al., 2013; Pope & Outwater, 1972).

Despite improved understanding of fracture propagation in bone, there is limited integration between sub-disciplines of its relationship with chop marks, specifically those fractures extending from the floor of the chop mark. Fracture propagation research often focuses on BFT, PT, and sometimes SBFT as well as the resulting radiating and concentric fractures from those categories of trauma (Kieser et al., 2013). The qualitative or quantitative study of fracture patterns, known as fractography, has more recently been integrated into the macroscopic study of bone in forensic contexts and is a method of "… accurate failure analysis based on the interpretation of microscopic fracture surface features that reveal the direction of crack propagation…" (Christensen & Hatch, 2019; Scherrer et al., 2017, p. 600).

2 | MATERIALS AND METHODS: A CASE STUDY OF FRACTURING FROM THE FLOOR OF CHOP MARKS

2.1 | Case study materials

The assemblage known as the "Weymouth Ridgeway Vikings" consists of a unique collection of individuals (MLNI = 47 (cranial) and 52 (post-cranial)) discovered in a mass grave in 2009 (Loe et al., 2014). All individuals for whom sex could be determined were male and the majority of the individuals were between 18 and 35 years of age (Boyle, 2016; Loe et al., 2014). Through radiocarbon dating and isotopic analysis, the individuals were found to date from 1045 ± 19 BP (calibrated date 970–1025 CE, 95.4% confidence) and to be of northern European and Scandinavian origin (Chenery et al., 2014; Loe et al., 2014). These individuals were decapitated and the osteological and contextual evidence suggests that this was the result of systematic executions.

The skeletons exhibit extensive SFT to the crania, mandibles, cervical vertebrae and upper limbs, some of which was not directly associated with decapitation. It is probable this SFT all comes from the same incident, which involved bladed weapons impacting with high amounts of force, resulting in the extensive injuries seen, both in the form of chop marks and resultant fractures. An absence of evidence for weathering and animal gnawing, and good survival of extremities, indicates that the individuals were buried shortly after their deaths. The preservation of the collection is good to excellent for the majority of the individuals, with little cortical surface damage.

Weaponry at the time could be very high quality if made by good smiths and the weapons used were similar between the Vikings and the Anglo-Saxons (Williams, 2014). Swords, axes, seaxes, and spears were commonplace in warfare (Pedersen, 2008; Underwood, 1999; Williams, 2014). In this collection, the majority of the chop marks are very clean and any SFT that retains its v-shaped profile is usually no more than 2 mm wide, as measured in the current study by digital calipers and on 3D point cloud data (via CloudCompare). This would suggest a thin, but heavy blade. It is suspected that most of the chop marks were made with similar blades, likely swords because of overall wound characteristics, associated radiating fractures and lesions crossing adjacent bones or bone regions (Loe et al., 2014). There are a set of smaller, incised cut marks, mainly on the cervical vertebrae, with similarly shaped cross-sectional profiles which mainly differ in overall size (width, depth).

Swords of the period were typically single-handed and double-edged, though single-edged blades have been found. They were often between 80 and 95 cm in length and good quality swords would be made with steel, some of which might be pattern-welded (Fedrigo et al., 2018; Hjardar & Vike, 2016; Pedersen, 2008; Underwood, 1999; Williams, 2012; Williams, 2014). These swords were typically designed for chopping rather than for thrusting, and would create longer and straighter chop marks than the axes of the time (Williams, 2014).

Axes were also commonplace in the Viking world, both as a tool and a weapon (Hjardar & Vike, 2016; Pedersen, 2008; Williams, 2014). Often axes have a thicker blade, making them less likely to have created the marks in this collection, however there were some axes at the time with very thin edges. It is possible that a thin axe, such as a "Dane axe" or "broad axe", produced the marks. It is not known whether the use of such axes in warfare predates the reign of Cnut and his heirs (1016–1042) (Williams, 2014). On balance, it seems more likely that swords were used in the process of decapitation.

2.2 | Case study methodology

This collection was first examined following excavation by a commercial archeological unit, Oxford Archaeology Ltd. and a comprehensive monograph was produced (Loe et al., 2014). This initial analysis provided detail of the extensive range of violence-related injuries that were apparent amongst the assemblage. During this original analysis, the osteoarchaeologists identified cut and chop marks macroscopically, with good, natural light, turning the bone to examine it in all angles in respect of the light and used a hand lens (up to ×20 magnification). As is standard practice in macroscopic osteological analyses, measurements were taken using vernier calipers with the purpose of augmenting the record of wounds observed, rather than capturing every measurement in high precision.

The current project involves further analysis in the form of a dedicated reappraisal of the SFT applying recent advances in technology (Tamminen et al., 2019). This involves photographing the chop mark surfaces with a macro camera lens (Nikon D810; AF-S Micro NIKKOR 60 mm f/2.8G ED), which helped highlight the differences in surface texture between the chop marks and the resultant fractures. These images were then enlarged to further increase the magnification

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TABLE 3 A checklist of recommended details which should be recorded when investigating chop marks and residual energy dispersal (RED) fractures in sharp-force trauma analysis

Detail	Chop marks	RED fractures
Identification of incised or shaved (further sub-categories can be used if required)	X	
What bone and location on the bone, including orientation in anatomical position	X	X
Location compared to chop mark		X
Associated chop marks on adjacent bones	X	
Dimensions	X	X
Direction and angle of impact	X	
Images with scale	X	X

available if the extent of the chop mark was unclear. Close-range 3D photogrammetric models of the chop marks were also created, allowing for digital investigation (via Agisoft Metashape at high resolution, methods detailed in Tamminen, 2022). In addition to making qualitative observations about the SFT, some chop mark 3D models were measured through the open-source freeware CloudCompare. Dense point clouds were used rather than mesh models to avoid interpolation between points for any measurements (See Figure S1 for an image of one of the 3D models). Manual and digital measurements were previously compared in a pilot study process to check whether there was any statistical difference; none was found (Tamminen, 2022). In addition, a digital microscope (Keyence VHX-5000) was used in the early stage of the project using magnification of ×30–50 which allowed for further qualitative observations of the chop and fractures surfaces.

Changes in surface texture, changes in angle or trajectory of the chop, and the overall shape or curvature of chop and adjacent fractures were examined using both a hand lens and a camera lens and recorded qualitatively. The methods employed involved examining the features set out in Table 3.

The chop marks with no taphonomy or post-mortem damage were analyzed first to identify specific characteristics whilst minimizing the risk of confounding factors (i.e. cortical damage). After this, an iterative process was used, where chop marks and associated fractures with increasing amounts of taphonomic or other damage (until the damage was too great to analyze with any confidence) were examined in order to delineate the edges of the chops compared to the fracture that arose at the same time. In this way, it became clear that it was important to denote the two distinct portions to the SFT (a chopped aspect and a fractured aspect) and that the use of digital analysis through photogrammetry was a vital tool for doing so.

3 | RESULTS

It is important to state that it is not the intention of the current article to imply that the previous measurements were incorrect. The measurements published following the initial analysis were both as precise and accurate as required for their purpose (a macroscopic osteological analysis). Rather, this article notes that, importantly, the respective SFT features can be divided into portions caused by the slicing action of the blade and portions caused by subsequent microfracturing. The relative proportions of damage to the bone coming under these two definitions would lend itself to further exploration by experiment.

In the current project, the most frequent additional contributions to the original analysis were that macroscopically, chop marks appeared longer because the resultant fracturing was included in the initial measurement of the chop mark. In these cases, the fracturing was very linear and therefore, when viewed without the aid of a macro camera lens, appeared as an extension of the chop mark, thus demonstrating the value of undertaking a higher resolution analysis with digital assistance (Figure 6). This highlights both the importance of using magnification and photogrammetric modeling and revisiting collections to reappraise trauma to learn more (Blumenschine et al., 1996). To raise awareness of this potential issue, a new term is proposed for these fractures and some of the characteristics are outlined in the following sections.

The term “Residual Energy Dispersal” fractures, or RED fractures, has been given to the fractures propagating from the floor of the chop marks. These fractures have been given a different name than the ones originating from BFT and PT in order to help draw attention to them and because the fracture initiation process in blunt-force trauma and these fractures propagating from the floor of chop marks is different. Although of similar origin to the radiating fractures associated with BFT and PT, the force transmitted through the bone in SFT is concentrated on a far smaller, and very linear area, thus leading to a “prying” action where the blade forces the bone apart and the fracture propagates ahead of the blade, an aspect not seen in BFT. The initiation of the fractures will, therefore, be different, despite the fact that the intrinsic fracture properties of bone remain the same, resulting in SBFT and/or RED fractures.

Differences were seen between some of the RED fractures, specifically those seen in cortical and trabecular bone, due to the differences in the nature of the blow and the bone itself. These fractures appeared to have a peri-mortem appearance to them, for example they have smooth surfaces, similar patination to the cortex of the bone, and some peeling at the fracture margins (Łukasik et al., 2019). Additionally, they were often directly connected to chop marks. Some similar-looking fractures were seen without directly associated chop marks, but these were often incomplete due to post-mortem damage. It is possible that some of these had also been related to chop marks. Table 4 details some of the important characteristics of RED fractures and the key features for differentiating between the fracture and a chop mark (Figure S1). Overall, surface texture and angle were the two most helpful features in distinguishing where a chop mark transitioned into a fracture.

RED fractures will not exist in all circumstances, however, since they can be long, it is important to note whether measuring the full SFT (chop mark and RED fracture) or just the chop mark when

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FIGURE 6 This figure demonstrates a portion of a right mandible with sharp-force trauma (SFT) denoting the chop mark (white arrow) and the residual energy dispersal (RED) fracturing propagating from it (white arrowheads) with Inset (a) highlighting the change in angle between the chop mark and RED as well as the difference in outline (smooth vs rough) and inset (b) showing the differences in surface texture between the chop mark (blue) and RED fracturing (red)

TABLE 4 The characteristics of residual energy dispersal (RED) fractures in cortical and trabecular bone, visually examined using magnification and, where possible, 3D digital models (further information in Figure S1)

Characteristic	Description	Cortical bone	Trabecular bone
Surface texture	The appearance and amount of the changes in topography across the fracture	Relatively smooth macroscopically, some unevenness, no shine Microscopic appearance is rougher than macroscopic appearance, small undulations, appearance of delamination (see Li et al., 2013 Figure 6)	Trabeculae broken approximately in a plane, uneven Often easier to identify if some cortical bone is present around the edge
Edges	The appearance of where the fractured surface ends and the unaffected cortical surface begins	Relatively smooth macroscopically with potential undulations More irregularities are noticeable macroscopically	N/A—edges are cortical bone unless otherwise damaged
Angle	The appearance of the profile of the surface at the junction of the chop and the fracture	Often a slight change from the angle of the chop mark Similar "fracture paths" are often seen between multiple bones if they are struck in similar locations	Often a slight change from the angle of the chop mark
Shape	The appearance of the profile of the fractured surface	Rectilinear or slightly curvilinear, not smooth	Rectilinear or slightly curvilinear, not smooth

analyzing SFT. Table 5 contains five examples of the measurements obtained when the entire SFT is included and when just the chop mark is included. The SFT measurements were taken manually in the original study with the purpose of preservation by record and the chop mark measurements were taken digitally in the current study. Due to the differential purposes and methods of these studies, statistical comparison has not been performed. The magnitude of the differences underlines the importance of considering this type of

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TABLE 5 The variation seen when measuring the entire sharp-force trauma (chop mark and residual energy dispersal [RED] fracture) and when measuring the chop mark without RED fracture (all measurements in mm)

SK	Location	SFT length[a]	Chop mark length[b]
3710	L Mandible (gonial angle)	53.8	10.8
3711	R Mandible (inferior corpus)	33.3	23.2
3711	L Mandible (gonial angle)	41.0	28.7
3759	R Mandible (gonial angle)	30.1	28.3
3761	R Mandible (inferior corpus)	36.0	12.6

[a] Manual measurements with vernier calipers.
[b] Digital measurements from a photogrammetric model in CloudCompare.

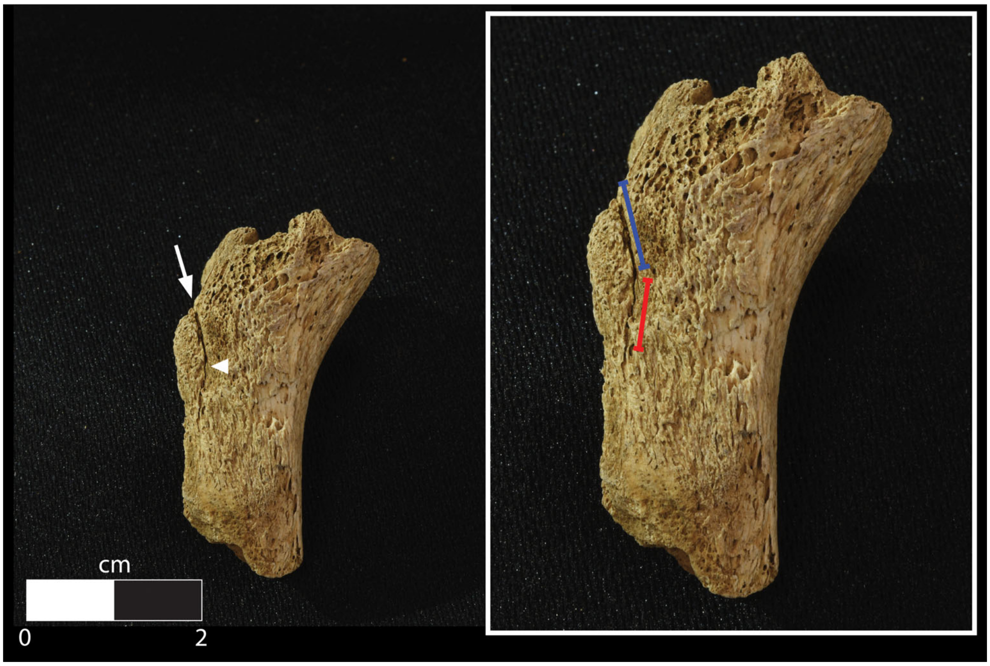

FIGURE 7 An example of a coracoid process of a right scapula with sharp-force trauma (SFT) where the chop mark has penetrated part way into the bone (white arrow) and was subsequently extended by residual energy dispersal fracturing, the beginning of which is visible by the change in angle (white arrowhead). The inset shows the delineation of the two with colors, showing the fracturing in red and the chop in blue

fracturing both independently and under the umbrella of SFT, as well as the importance of clearly indicating what is being measured.

4 | DISCUSSION

The term RED was assigned due to the mechanisms by which these fractures arise (Figure 7). It is proposed that these fractures be considered in addition to chop marks themselves within the category of sharp-force trauma, rather than as a separate entity. Both the chop mark and any resultant fracturing, including RED fracturing, should be considered under the umbrella of SFT, or SBFT if appropriate.

4.1 | Mechanisms of RED fractures

There are two major mechanisms by which blades could cause such fractures. The first of these is the propagation of the fracture ahead of the blade from the force itself, or with the blade acting like a wedge, prying the two bone surfaces apart. This is also supported by research that has shown that there is an area of micro-damage ahead of the tip of the crack as it propagates (Voide et al., 2009). The second factor is the removal of the blade, especially if there is a twisting motion involved. Both factors are considered to be Mode I, therefore the actual failure of the bone would likely happen in a similar manner in both cases and it may not be possible to ascertain how much each mechanism contributed (Lawn, 1993). Both factors result in the two parts of the bone on either side of the blade being forced apart. In some instances, the bone will break all the way through, and in others, just a small fracture will appear at the base of the chop mark.

An additional consideration that influences all cases is taphonomy (see Pokines et al., 2022). Post-mortem circumstances such as decomposition, cycles of wetting and drying, and loss of water from bone can both cause and exacerbate fractures. The interaction of post-mortem factors and these fractures is something that should be further investigated as the ability to distinguish if fractures were solely due to trauma, due to trauma and augmented by taphonomy, or solely due to taphonomy would be highly useful when investigating trauma in both osteoarchaeology and forensic anthropology.

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4.2 | Implications for future and current research

For the study of such fractures to further progress, experimental studies are required in which more variables are known (e.g., Karr & Outram, 2012, 2015). Collections, such as the one used in this study, are helpful because the burial context was consistent throughout the collection and the weapons were likely similar, thus increasing consistency across the collection. Experimental studies could help show what, if any, differences in fracturing there are based on weaponry, the geometry of the bone, and the subsequent burial environment, to name a few. This will help discover more about the nature of the fractures as well as how much information they can provide about their creation, information that is useful when studying both human skeletal remains and faunal remains (e.g., butchery studies).

Within the field of osteoarchaeology, future examination into the impact of different weapon categories (e.g., sword, axe, and knife) on the characteristics of RED fractures could allow for more information to be gathered about the weaponry used in the event. Similarly, this allows for the refinement of the directionality of the chop. As seen in the case study, the identification of RED fractures supported the original finding of a chaotic event with decapitations from multiple directions, rather than a situation where each individual was hit in an identical manner.

The ability to identify directionality of the chop through the location of these fractures in relation to the chop marks could also have implications in the field of forensic anthropology, as rectifying the positioning of the weapon relative to a victim could help support or disprove a proposed sequence of events.

Experimental studies could also allow for differences in characteristics between RED fractures and any extension of said fractures due to post-mortem effects to be explored. Further increasing the magnification (e.g. digital microscopy or scanning electron microscopy) could be advantageous for such studies to investigate if there are differences in fracture characteristics between these types of fractures that might be evident, allowing further clarification of etiology.

5 | CONCLUSION

This collection provided an opportunity to study SFT on human remains on a much larger scale than is commonly seen. Since the trauma comes from the same event, this collection provides the opportunity to analyze what is essentially the results of a repeated SFT experiment. The assemblage was excavated and analyzed to an exceptionally high standard (see Loe et al., 2014), which, in combination with the unique nature of the collection, makes it an invaluable resource for trauma studies.

Through the appraisal and reappraisal of the SFT of the Weymouth Ridgeway Vikings, it has become evident that it is important to highlight the existence of the resultant fractures propagating from the base of chop marks and the importance of the use of digital techniques, such as photogrammetry, to identify their presence. As such, it is proposed that these fractures are given a name to differentiate them from secondary fracturing from BFT or PT as they are initiated differently. In RED fractures from chop marks, the force tends to continue in the same direction as the blow, traveling along the longitudinal axes of the osteons. Conversely, in BFT or PT, the fractures tend to radiate out and away from the impact site. Fractures near chop marks should be properly investigated to determine if they are associated with the chop mark. It is important to include them in the analysis of SFT whilst acknowledging they are not part of the chop mark itself. This differentiation, and the use of digital analyses, will aid a more comprehensive investigation of the trauma on an individual and the potential events that occurred.

Delineating RED fractures from the chop marks themselves can affect the quantity, pattern, and interpretation of the trauma. Additionally, their existence could indicate that SFT was present, even if no evidence of the chop mark itself remains; though how easy they are to be diagnose without a visible chop mark needs investigation. It is, therefore, important not to over-interpret RED fractures. However, it is important to discuss them in the contexts of SFT analysis, taphonomy, and bone fracturing as they straddle all these topics. This type of fracture is currently under-discussed and, whilst further research will help create a more precise definition for these fractures, they have the potential to augment knowledge of events involving SFT if given proper consideration.

AUTHOR CONTRIBUTIONS

Heather M. Tamminen: Conceptualization (lead); formal analysis (lead); investigation (equal); methodology (lead); visualization (lead); writing – original draft (lead); writing – review and editing (equal). **Andrew L. J. Ford:** Supervision (equal); writing – original draft (equal); writing – review and editing (equal). **Kate Welham:** Supervision (equal); writing – original draft (equal); writing – review and editing (equal). **Louise Loe:** Formal analysis (equal); investigation (equal); writing – original draft (equal); writing – review and editing (equal). **Helen Webb:** Formal analysis (equal); investigation (equal); writing – original draft (equal); writing – review and editing (equal). **Angela Boyle:** Formal analysis (equal); investigation (equal); writing – original draft (equal); writing – review and editing (equal). **Martin J. Smith:** Conceptualization (equal); formal analysis (supporting); methodology (supporting); supervision (lead); writing – original draft (equal); writing – review and editing (equal).

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DATA AVAILABILITY STATEMENT

The collection is curated by the Dorset Museum. The original analysis has been published and is available (Loe et al., 2014) and the PhD thesis containing the subsequent analysis will be available online after a period of embargo.

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