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ORIGINAL ARTICLE

Radiological detection of sharp force skeletal trauma: an evaluation of the sensitivity of Lodox in comparison to CT and X-ray

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Abstract
Victims of violent crime often have evidence of sharp force trauma (SFT) which needs to be examined to accurately investigate these cases. The abilities of CTs, X-rays, and Lodox to detect skeletal SFT defects and the minimum number of impacts were assessed, as were their abilities to macroscopically interpret SFT with the aim of identifying the class of weapon used. Ten pigs were, post-mortem, stabbed using a kitchen knife on one side of the body and chopped using a panga on the other side. They were then scanned and macerated. The number of SFT defects, type of SFT, and minimum number of impacts identifiable osteologically were recorded, as well as when using each imaging modality. CTs were most sensitive for detecting stab and chop defects (56.7% and 78.3%, respectively) and the minimum number of impacts (82.8%), while X-rays were least sensitive (17.2% for stab wounds, 46.5% for chop marks, and 43.5% for impacts). Lodox detected 26.8% of stab defects, 59.3% of chop marks, and 58.4% of impacts. The type of SFT for more than 70.0% of identified defects was correctly classified using all methods, while only Lodox had moderate sensitivities for stab wounds (52.4%). When radiological assessments of skeletal SFT are required, CTs should be performed, but Lodox can be used as an alternative. However, dry bone analyses still produce the best results and should be performed whenever possible. Macroscopic interpretations of skeletal SFT to broadly determine the class of weapon used is possible radiologically.

Keywords Sharp force trauma · Radiological sensitivities · Computed tomography (CT) · X-ray · Low-dose full-body X-ray (Lodox)

Introduction

Individuals with evidence of sharp force trauma (SFT) are relatively common in both clinical and forensic settings. SFT is trauma produced as a result of bevelled, edged, or pointed instruments [1], resulting in incisions, punctures, or clefts on the bone [2]. Of the 21,325 murders reported in South Africa in 2019/2020, 6354 (29.8%) were the result of SFT, while 17.2% of all attempted murders and assaults were committed using sharp instruments [3]. Between 2015 and 2017, 7.1% of all cases at the Johannesburg Forensic Pathology Services involved sharp force injuries (C. Keyes, personal communication), and from 2016 to 2020, 10.7% of forensic anthropological analyses conducted at the Human Variation and Identification Research Unit at the University of the Witwatersrand had evidence of SFT. Between 18.9% [4] and 20.9% [5] of patients presenting in South African emergency trauma centers have sharp force injuries. The detection and analysis of these injuries, specifically to the skeletal system, is crucial in optimizing patient care or establishing the circumstances surrounding death.

The examination of the specific characteristics of the SFT can add further information regarding the traumatic event, such as the class of weapon used, which could aid in identifying the murder weapon or the instrument used

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in post-mortem dismemberment cases [6]. For example, narrow defects such as cuts, incisions, or punctures in the bone are generally a result of stabbing trauma with weapons such as knives [2, 7], while wide defects with bone wastage and chattering, and other sharp-blunt characteristics such as fracturing and crushing of the bone, are often the result of hacking trauma with weapons such as axes, hatchets, or machetes [2, 8, 9]. Saws are often used in cases of post-mortem dismemberment and analyzing the characteristics of the kerf wall and floor, such as the striations made by the instrument, can assist in determining the class of saw used [6, 10, 11].

Soft tissue injuries resulting from SFT are generally easy to detect during clinical and forensic examinations and are often used to help locate sites of osteological trauma. As an alternative to dissecting or macerating the remains to examine SFT, which is time-consuming and labour-intensive and which cannot be performed in living individuals, radiological imaging can be used. In cases of burning, where skeletal remains are charred and therefore extremely fragile, conducting a dry bone analysis is not always appropriate as the bones may fragment and crumble [12]. In these cases, soft tissue may also become charred and adhere to the bone surface, which could obscure any trauma beneath this tissue [12, 13]. The virtual examination of skeletal trauma in these cases is therefore invaluable.

While the radiological examination of soft tissue injuries as a result of SFT has been widely assessed [14–19], as has the use of micro-computed tomography (micro-CT) to analyze SFT characteristics on the bone [20–24], only a handful of studies have evaluated the use of imaging methods to detect and macroscopically interpret SFT to bone. Schnider et al. [15] assessed SFT in 12 individuals using both autopsy and radiological means and found that CT detected 100% of SFT osseous lesions detected during autopsy, whereas Thomsen et al. [16] noted that CT scans were more sensitive than autopsy in detecting skeletal fractures in cases of sharp-blunt trauma. Ampanozi et al. [25] used CT and magnetic resonance imaging (MRI) scans to virtually analyse SFT to the skull using a hatchet and found that many of the macroscopic features characteristic of the bone trauma caused by this type of weapon were easily identifiable radiologically, including bone crushing and fracturing. Furthermore, CT was found to be superior to autopsy in determining the exact number of bone fragments as a result of the SFT, as well as the presence of bone flaking at sites of trauma [25]. Other authors [26, 27] used 3-dimensional CT imaging to assess SFT to the skulls of surviving victims and reported that the weapons used to inflict the trauma, an axe and a hatchet, respectively, could be confirmed based on the characteristics of trauma visualized radiologically.

All previous studies [15, 16] evaluating the radiological detection of sharp force injuries to bone, however, have used autopsy results as the gold standard. In addition, the studies that have radiologically assessed the macroscopic characteristics of skeletal SFT were case studies [25–27], where the exact weapon used to inflict trauma was known prior to radiological imaging, and imaging was used to confirm the use of this weapon. Moreover, the sensitivity of conventional X-rays in the detection and interpretation of SFT has rarely been evaluated, while low-dose full-body X-rays (commonly referred to as Lodox) have yet to be assessed. Lodox is commonly used in South African hospitals [28, 29] and medico-legal laboratories [30] as a result of its fast-scanning times and low maintenance costs. It is therefore imperative to test the ability of Lodox scans to detect and interpret sharp force skeletal lesions in comparison to CT and X-ray.

As a result, a study that uses the dry bones rather than autopsy results as the gold standard would be novel, as would a study that includes the evaluation of Lodox in detecting skeletal SFT. In addition, research that is not a case study but that rather aims to distinguish between two or more possible classes of weapons based on certain macroscopic characteristics would also be novel. Therefore, the aim of this study was to compare the abilities of CTs, conventional X-rays, and Lodox scans in detecting skeletal defects as a result of SFT. In South Africa, kitchen knives and pangas, which are weapons similar to machetes, are among the most commonly used sharp instruments during incidences of violent crime [3]. These two weapons result in different types of osteological SFT; knives are generally used during incidences of stabbing, resulting in puncture or incision defects on bone [2, 7], while pangas are used to inflict hacking trauma, which causes sharp-blunt, chop defects on the bone [2, 8, 9]. As a result, an additional aim was to evaluate the suitability of these radiological methods to determine the type of SFT inflicted, either stabbing or hacking trauma, and by analyzing the macroscopic characteristics of the trauma, the class of weapon used (either a kitchen knife or a panga). These aims were achieved by comparing the results of the radiological examinations to what was observed on the dry bones.

Materials and methods

Experimental design

In order to accurately simulate the most common types of sharp force injuries seen in South Africa [3], a non-serrated kitchen knife and a panga were used to inflict SFT on ten deceased pigs (47–79 kg each), with one side of the body being subjected to stabbing trauma using the kitchen knife, and the other side hacking trauma using the panga (Animal Research Ethics Committee at the University of the Witwatersrand, Clearance Certificate Number

2019/04/27/O). Pigs were used since research has shown that pig bones are acceptable proxies for humans when studying sharp force skeletal trauma [31]. The kitchen knife was single-edged and non-serrated, with a stainless-steel blade measuring 163 mm in length and 28 mm in width. The panga had a curved carbon steel blade, measuring 652 mm in length and 112 mm in width. The side of the body on which each instrument was used to inflict trauma was not kept consistent in order to reduce bias but was recorded independently for each pig.

Each weapon was used to inflict between 1 and 10 strikes to each of the four body regions: the skull, the trunk (including the ribs and vertebrae), the forelimbs, and the hindlimbs. The number of strikes inflicted was not kept consistent in order to reduce bias and to keep the investigators blind to the exact number of strikes and/or lesions. This did not affect the calculations of sensitivity and specificity, which are described below, as the number of strikes inflicted were not assessed but rather the number of lesions present on the skeleton as a result of these strikes. It is important to note that some strikes may not result in any trauma, while others may only cause soft tissue trauma while leaving the skeletal elements intact. The same individual inflicted both types of trauma on each pig.

The radiological methods used to detect SFT included full-body helical CT scans, conventional X-rays of each body region, and full-body Lodox scans. Ventro-dorsal and left and right lateral images were taken using both conventional X-rays and Lodox. Milliampere-seconds (mAs) and kilovoltage (kV) were, respectively, 150–300 and 120 for CTs, 2–45 and 45–91 for X-rays, and 200 and 120 for Lodox. Slice thickness and slice increment were 3.0 mm and 1.5 mm, respectively, for CTs. After the pigs were scanned, they were skeletonized so that the dry bones could be examined as the gold standard. Cleaning of the remains during the maceration procedure was done extremely carefully, especially when using scalpels to remove the soft tissue, to ensure that no additional SFT was introduced to the remains.

CT (both 2-dimensional and 3-dimensional), X-ray, and Lodox images were analyzed using RadiAnt DICOM Viewer (version 2020.2.2). The number and location of skeletal sharp force defects evident in each body region was recorded for each type of radiological method, as well as for the dry bones. The number of defects present in each body region was added to obtain the total number of defects present.

The type of SFT was also recorded as either stabbing or hacking trauma. Following guidelines by numerous authors [2, 7–9], several macroscopic characteristics were considered when distinguishing between the two types of SFT. These traits are outlined in Table 1 [2, 7–9] and are illustrated in Figs. 1, 2, 3, 4, 5, 6, and 7. Bone wastage occurs when the sharp instrument is removed from the bone, resulting in bone fragments being separated from the main section of the bone [2, 9]. Chattering refers to the presence of bone chipping at the site of trauma [8]. For a more detailed description of these distinctive characteristics, please refer to [2, 7–9]. Based on the type of SFT, stabbing vs hacking, the class of weapon was assessed. The minimum number of strikes inflicted was also estimated by ascertaining which sharp force skeletal defects were likely the result of the same impact (Figs. 4 and 6). A minimum number was determined as some strikes may not have resulted in any osteological lesions.

Data analysis

In line with previous papers assessing the radiological detection of blunt force trauma (BFT) [32, 33], the sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) of each imaging method in identifying the overall number and location of sharp force defects, as well as the number and location of each type of SFT, was calculated by comparing these results against the results from the dry bone assessments. A radiological method's sensitivity is its ability to detect fractures that are also present osteologically, while its specificity is its ability to correctly determine that a bone does not have a fracture. PPV refers to the probability that a radiologically identified fracture is actually present osteologically, while NPV refers to the probability that a bone not determined to have a fracture virtually is indeed fracture-free osteologically. The sensitivity for estimating the minimum number of impacts was also calculated for each imaging method.

Table 1 Characteristics used to distinguish between stabbing trauma inflicted with a kitchen knife and hacking trauma inflicted with a panga [2, 7–9]

Stabbing trauma	Hacking trauma
Narrow defects (< 1.5 mm)	Wide defects (> 1.5 mm)
Cut marks and puncture wounds	Chop marks
Small nicks or notches in the bone cortex	Bisected and comminuted defects
Minimal bone wastage, chattering, flaking, crushing, and fracturing	Significant bone wastage, chattering, flaking, crushing, and fracturing
Hinge fractures	Sharp-blunt characteristics

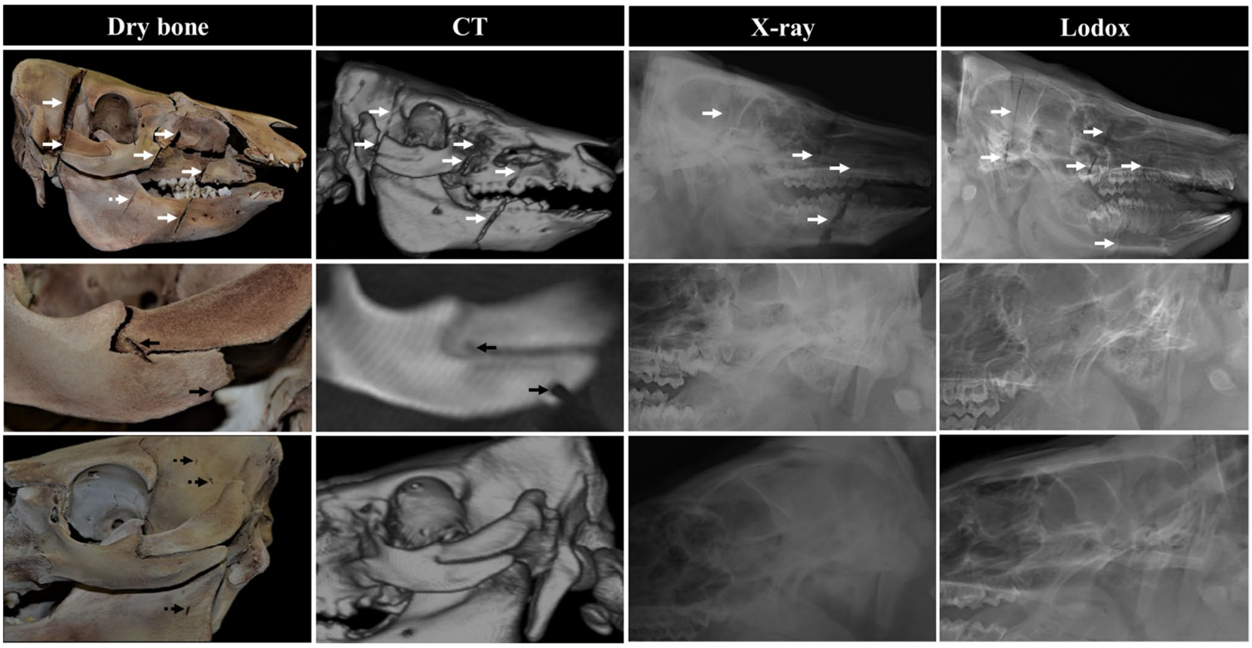

Fig. 1 SFT defects to the skull, as seen on the dry bone, CT, X-ray, and Lodox. Many of the wide chop marks (solid white arrows) were identified by all imaging modalities, but some of the narrower, shallower chop defects (dashed white arrow) were only detectable on the dry bone. Some of the small, puncture defects as a result of stabbing trauma (solid black arrows) were identified by CT, but not X-ray or Lodox in any radiographic view. However, other much smaller stabbing defects (dashed black arrows) were not identified by any radiographic method

Radiological examinations were only conducted 3 months after the infliction of trauma, scanning, and maceration, in order to reduce memory bias regarding the exact number of strikes inflicted to each pig, as well as which weapon was used on each side of the body. Dry bone examinations were only conducted after the radiological assessments had been completed. Two-way ANOVA tests were used to determine if the number of defects detected and the minimum number of strikes estimated using each radiological tool differed significantly from those recorded during the osteological examinations.

Intra- and inter-observer repeatability

A specialist radiologist with experience in forensic imaging read the CT, X-ray, and Lodox scans of five pigs to perform an assessment of inter-observer repeatability, while the primary investigator performed an intra-observer repeatability assessment by reading the scans of the same five pigs 1 month apart. Intra- and inter-observer agreement in the number of SFT lesions present in each body region using each radiological method was assessed, as was the type of SFT and class of weapon associated with each lesion. The level of inter- and intra-observer agreement was evaluated using Cohen's kappa. The two-way ANOVA and Cohen's kappa tests were performed using SPSS (version 26).

Results

Agreement between the number of defects and impacts detected by the primary investigator and the radiologist was substantial to almost perfect [34], ranging between 0.84 and 0.98 for CTs, 0.72 and 1.0 for X-rays, and 0.65 and 1.0 for Lodox. Intra-observer agreement was almost perfect, ranging between 0.81–0.93 for CTs, 0.89–1.00 for X-rays, and 0.92–1.00 for Lodox.

The highest sensitivities for detecting sharp force defects were achieved when using CT scans, which detected 292 (70.4%) of the 415 defects detected during the dry bone analyses, including 89 (56.7%) of the 157 stab wounds and 202 (78.3%) of the 258 chop marks. The lowest sensitivities were attained when using X-rays, which identified 35.4% of the total number of defects, 17.2% of stab wounds, and 46.5% of chop marks. Sensitivities for Lodox were 47.0%, 26.8%, and 59.3% for all defects, stab wounds, and chop marks, respectively. All methods were far more sensitive in detecting chop marks compared to stab wounds. Of the stab wounds detected by CT, 76 (85.4%) were correctly classified as stab wounds, while the remaining 14.6% were incorrectly classified as chop marks, and 165 (81.6%) of chop marks identified by CT were correctly classified as such. When using X-rays, 74.1% of stab wounds were correctly identified as stab defects, and 80.8% of chop marks were

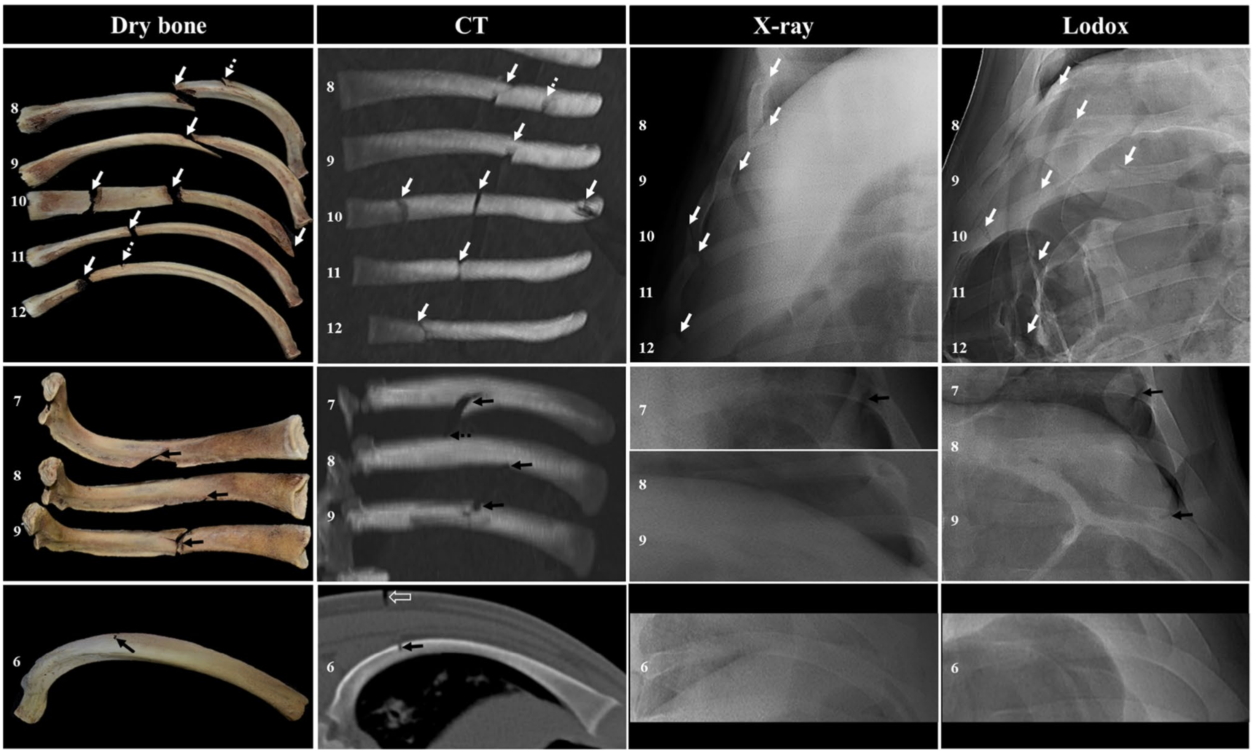

Fig. 2 SFT defects to the ribs, as seen on the dry bone, CT, X-ray, and Lodox. Many chop marks (solid white arrows) were easily identifiable by all radiological techniques, while some of the smaller chop marks (dashed white arrows) were either only detectable using CTs or on the dry bones only. Note the chattering, crushing, and fracturing of bone associated with the chop defects on ribs 8, 9, and 10 in row 1, which is visible using CT. Many stab defects (solid black arrows), especially those with associated hinge fractures and bone chipping (ribs 7 and 9, row 2), were identifiable using CT, X-ray, and Lodox. However, many of the smaller defects, visible as small nicks or notches in the bone cortex (rib 8 in row 2 and rib 6 in row 3) were only detectable radiologically using CTs. Note how skin incisions/lacerations (white arrow outline) often assisted in locating sites of underlying bone trauma (rib 6, row 3), but soft tissue injuries may also result in false-positive identifications (dashed black arrow) by creating radiolucent, linear lesions which can mimic fractures on the scans, but which are not present on the dry bone (rib 8, row 2)

indeed classified as chop marks. For Lodox, only 52.4% of stab wounds were correctly classified, while the remaining 47.6% were indeterminate or incorrectly classified as chop marks. However, 85.0% of chop marks detected by Lodox were correctly classified as such.

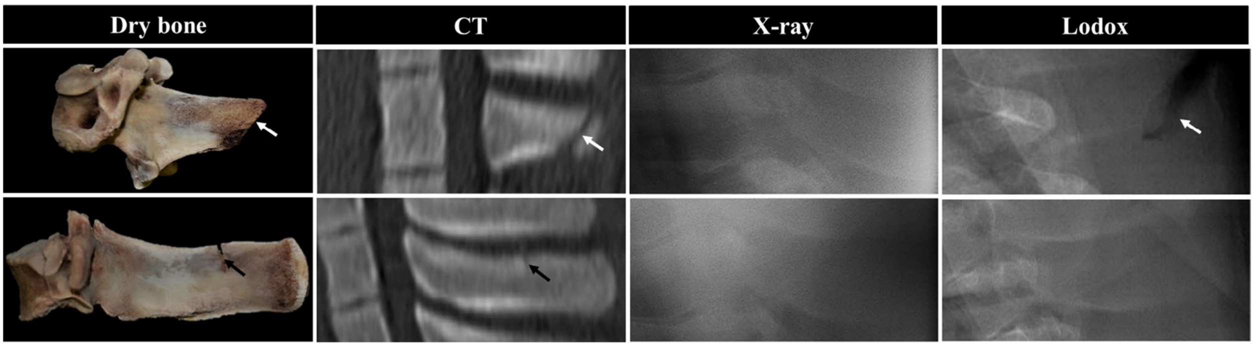

Fig. 3 SFT defects to the vertebrae, as seen on the dry bone, CT, X-ray, and Lodox. Chop marks (solid white arrows) could be identified using CTs and Lodox, but not using X-rays, while small incision defects as a result of stabbing trauma (solid black arrows) were often only identifiable using CTs

Fig. 4 Hacking trauma defects to the forelimb, as seen on the dry bone, CT, X-ray, and Lodox. Most chop marks as a result of hacking trauma (solid black and white arrows) were easily identifiable using all imaging modalities. However, some of the smaller chop defects (dashed black arrow) were only detectable on the dry bone. The solid black arrows show two separate defects, one to the distal epiphysis of the ulna and one to the distal shaft of the radius, that are the result of only one impact. Note bone wastage, chattering, and fracturing associated with the chop defect to the ulna (solid white arrows). Also note how soft tissue lesions (dashed white arrows) could result in false-negative fracture identifications using X-rays and Lodox, as skeletal defects could be mistaken as only soft tissue defects

Overall specificities were high for all radiological methods, ranging between 92.9% and 97.2% for CTs, 97.5% and 99.1% for X-rays, and 92.9% and 97.6% for Lodox. PPVs and NPVs were also generally high (CTs: PPVs 77.4–97.6% and NPVs 82.9–92.9%; X-rays: PPVs 79.4–93.0% and NPVs 69.8–85.9%; Lodox: PPVs 68.9–85.0% and NPVs 73.2–87.4%).

The sensitivities of each imaging modality for detecting sharp force defects in each body region are presented in Fig. 8, together with the two-way ANOVA results. CTs consistently had the highest sensitivities for detecting both stab wounds and chop marks in all body regions, while X-rays were consistently the least sensitive (Figs. 1, 2, 3, 4, 5, 6, and 7). When considering the overall number of sharp force defects, as well as chop marks, sensitivities were highest for the fore- and hindlimbs for all methods, while sensitivities for detecting stab wounds were highest for the ribs for CT and Lodox, and highest for the hindlimbs using X-rays. The lowest sensitivities for all types of sharp force defects were noted for the vertebral region, except when detecting stab wounds using CTs, for which the hindlimbs had the lowest sensitivity. In general, sensitivities for all methods in all body regions were higher for detecting chop marks compared to stab wounds (Fig. 8).

Skull defects were considered as either cranial or mandibular defects. CTs were most sensitive, detecting 69.6% of all cranial defects (50.0% of stab wounds and 78.1% of chop marks) and 58.1% of all mandibular defects (52.9% of stab wounds and 64.3% of chop marks). Sensitivities were lowest for X-rays, which detected 30.4% of cranial defects (14.3% stab and 37.5% chop) and 25.8% of mandibular defects (0.0% stab and 57.1% chop). Lodox detected 50.0% of cranial defects (35.7% stab and 56.3% chop) and 35.5% of mandibular defects (17.6% stab and 57.1% chop). Specificities for skull defects were above 87.0%, PPVs above 76.0%, and NPVs above 50.0% for all methods.

Fig. 5 Stabbing trauma defects to the forelimbs, as seen on the dry bone, CT, X-ray, and Lodox. Many puncture and incision defects as a result of stabbing trauma were detectable using all imaging methods (solid white arrows), while some were only identifiable using CT and Lodox (solid black arrows). Note how soft tissue lesions assist in locating sites of bone trauma in X-ray and Lodox scans (solid white arrows)

Rib defects were classified either as vertebral end, shaft, or sternal end. CTs had the highest sensitivities for all rib locations, identifying 64.0% of all vertebral end defects (60.0% of stab wounds and 66.7% of chop marks), 72.6% of shaft defects (74.1% of stab wounds and 71.4% of chop marks), and 52.2% of sternal end defects (25.0% of stab wounds and 57.9% of chop marks). X-rays had the lowest sensitivities, with only 16.0% vertebral end (0.0% stab and 26.7% chop), 37.1% shaft (37.0 stab and 37.1% chop), and 34.8% sternal end defects (0.0% stab and 42.1% chops) being identified. Lodox detected 32.0% of vertebral end defects (20.0% of stab wounds and 40.0% of chop marks), 48.4% of shaft defects (44.4% of stab wounds and 51.4% of chop marks), and 39.1% of sternal end defects (25.0% of stab wounds and 42.1% of chop marks). All modalities had specificities above 93.0% for rib defects, and NPVs were above 84.0% for all modalities, except when using X-rays and Lodox to detect the overall number of rib defects (73.0% and 76.0%, respectively). PPVs for rib defects were much more variable, ranging between 50.0% and 91.8% for CTs, 0.0% and 100.0% for X-rays, and 33.3% and 90.0% for Lodox.

For vertebral defects, specificities were above 96.0% and NPVs above 87.0% for all radiological tools. PPVs for vertebral defects ranged between 50.0% and 88.9% for CTs and between 25.0% and 50.0% for Lodox. PPVs could not be calculated for X-rays as no true-positive or false-positive identifications were made using this method.

For forelimb defects, specificities were above 79.0% and PPVs above 66.0% for all imaging techniques. NPVs ranged between 66.7% and 94.2% for CTs, 48.0% and 80.8% for X-rays, and 49.6% and 83.0% for Lodox. For the hindlimbs, specificities were above 93.0% and PPVs above 75.0% for all modalities. NPVs for hindlimbs ranged between 84.3%

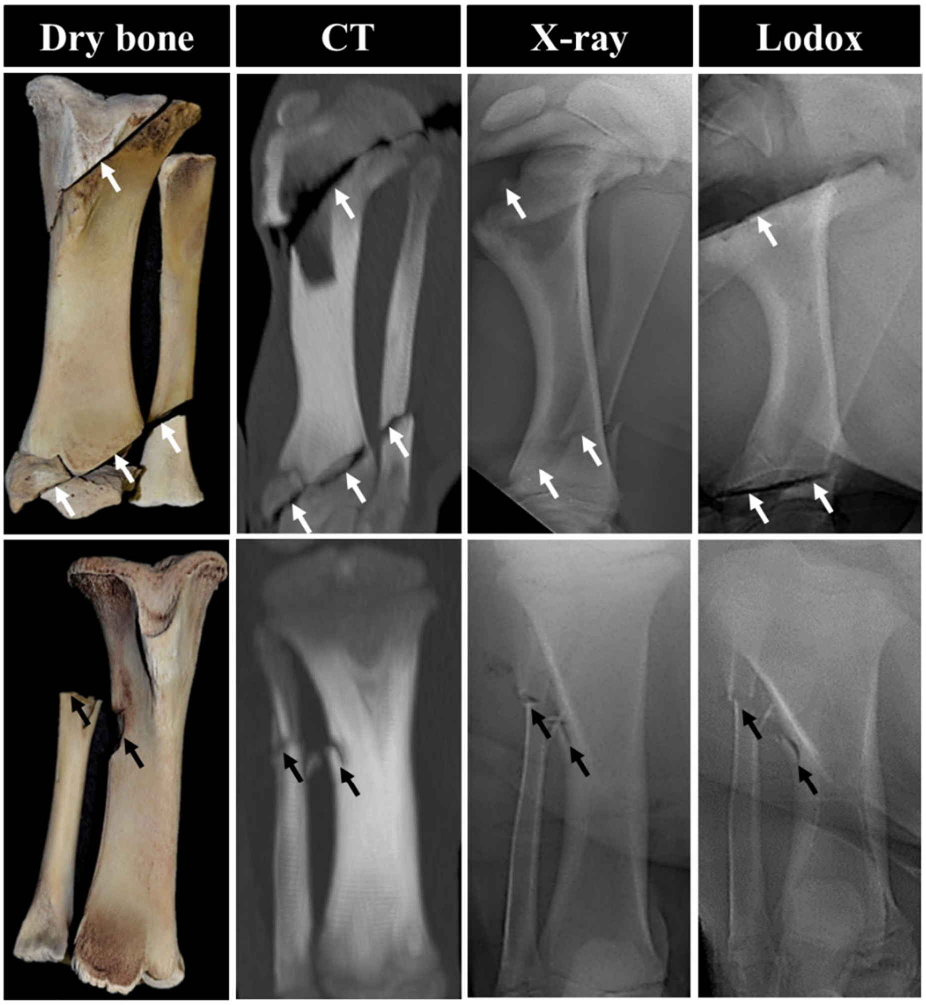

Fig. 6 Hacking trauma defects to the hindlimbs, as seen on the dry bone, CT, X-ray, and Lodox. Most chop marks from hacking trauma (solid white and black arrows) were identifiable using all imaging modalities. The solid white arrows show four separate defects (one proximally and three distally), that are the result of two impacts (one proximally and one distally). The solid black arrows show two separate defects that are likely the result of the same impact. Note complete bone bisection of the proximal tibia and distal fibula (solid white arrows), as well as bone chattering associated with the chop defects to the tibia and fibula (solid black arrows)

and 93.8% for CTs, 70.4% and 90.2% for X-rays, and 77.4% and 90.3% for Lodox.

Of the 308 impacts (154 stab and 154 chop) that were found during the dry bone analyses, 82.8% (70.8% stab and 94.8% chop) were correctly identified using CTs, 43.5% (21.4% stab and 65.6% chop) using X-rays, and 58.4% (35.1% stab and 81.8% chop) using Lodox.

Discussion

The accurate detection and interpretation of skeletal defects as a result of SFT has both clinical and forensic implications. This study assessed the abilities of CTs, X-rays, and Lodox to detect sharp force skeletal defects in pig carcasses subjected to SFT, as well as the possibility to interpret the macroscopic characteristics of these defects in order to determine the type of SFT and, as a result, the class of weapon used. A similar study assessing the sensitivities of these radiological methods in detecting fractures as a result of blunt force trauma (BFT) was previously performed [33], and therefore, sensitivities for detecting SFT and BFT in the various body regions are compared.

The highest sensitivity for detecting the overall number of sharp force skeletal defects was achieved using CTs (70.4%), which was lower compared to that reported by Schnider et al. [15], who found CTs to have a sensitivity of 100.0% for detecting skeletal SFT. However, CT results in that study were compared against autopsy findings as the gold standard, rather than an analysis of the cleaned skeletal remains as in the present study. Since it has been shown that autopsy is sometimes insensitive for detecting skeletal trauma [16, 35, 36], a 100.0% detection rate using CTs as reported by Schnider et al. [15] should be treated with caution. The overall sensitivities in the present study are much higher than those for detecting fractures in pigs as a result of BFT, with a sensitivity of 55.2% reported for CTs, 25.8% for X-rays, and 29.3% for Lodox [33].

Two types of SFT were inflicted in the present study—stabbing trauma and hacking trauma. All imaging modalities

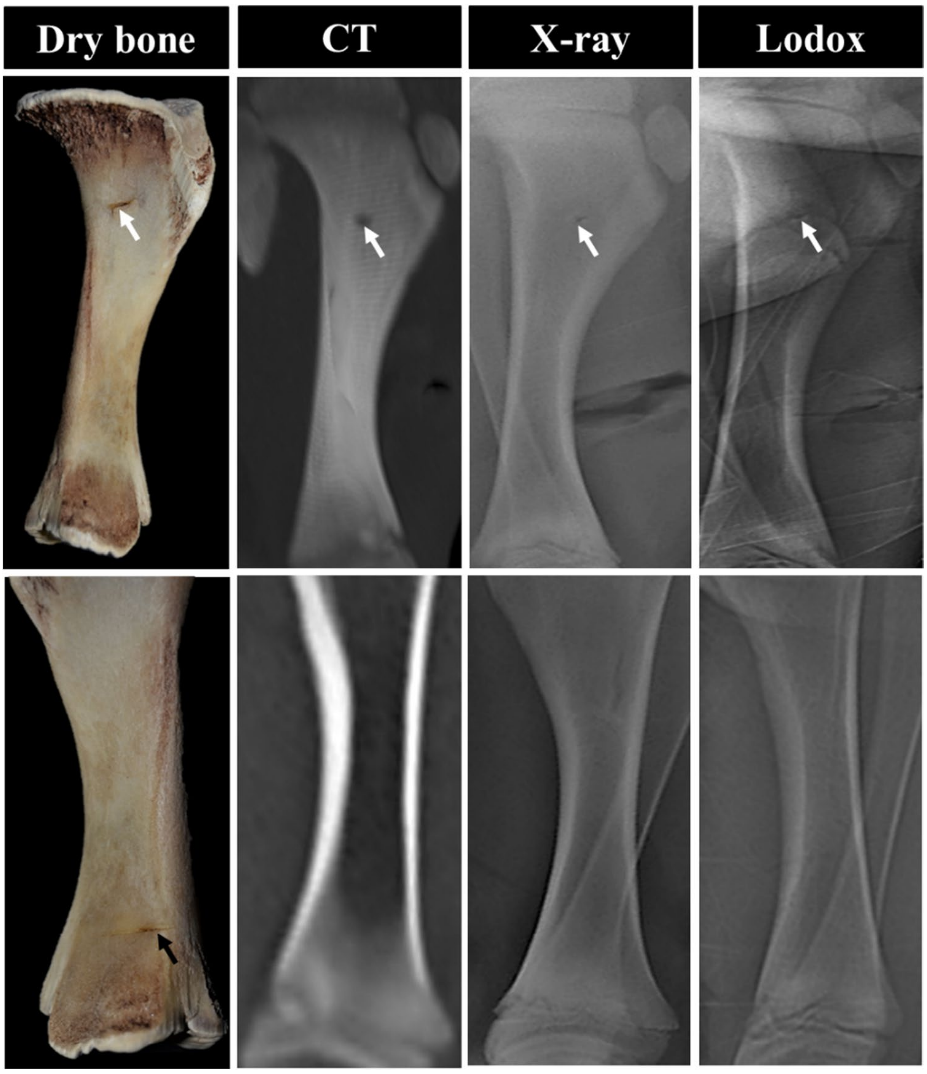

Fig. 7 Stabbing trauma defects to the hindlimbs, as seen on the dry bone, CT, X-ray, and Lodox. Some puncture defects as a result of stabbing trauma were detectable using all imaging methods (solid white arrows), while some of the shallower cut marks (solid black arrow) were not detectable radiologically using any imaging method

are much more sensitive for detecting chop marks as a result of hacking trauma compared to defects as a result of stabbing trauma. This is likely because hacking trauma often results in much larger, wider defects with significant trauma to the bone, including bone wastage, chattering, crushing, flaking, and fracturing (Figs. 1, 2, 3, 5, and 7). In contrast, defects associated with stabbing trauma are often narrow, small punctures, or cut marks in the bone, resulting in very small nicks or notches in the bone cortex (Figs. 1, 2, 3, 4, and 6). The detection of these small defects is difficult and depends on the resolution and settings of the radiological tool used [37]. Using thinner CT slices may therefore increase these detection rates. However, difficulties in identifying very small SFT defects have also been found to be the case during examinations of dry bone specimens [38].

The low to moderate sensitivities for detecting stab defects have specific implications for decomposed remains whereby the soft tissues may be too decomposed for stab wounds to be visible on the surface and would obscure the stab defects on the underlying bone. In such cases, where only radiological imaging is used, these wounds may be easily overlooked.

Based on the macroscopic characteristics outlined in Table 1, CT and X-ray are highly sensitive for correctly determining the type of SFT inflicted, and therefore, the broad class of weapon used (in this case, a kitchen knife for inflicting stabbing trauma, and a panga for inflicting hacking trauma). However, Lodox is only moderately sensitive for distinguishing stabbing trauma. This may be due to superimposition of structures, as well as the presence of post-mortem gas, which makes small defects like stab wounds difficult to detect. Several other researchers also found that hacking trauma was easy to distinguish using CT scans, which could therefore be used to confirm the class of weapon involved (i.e., an axe or hatchet) [25–27].

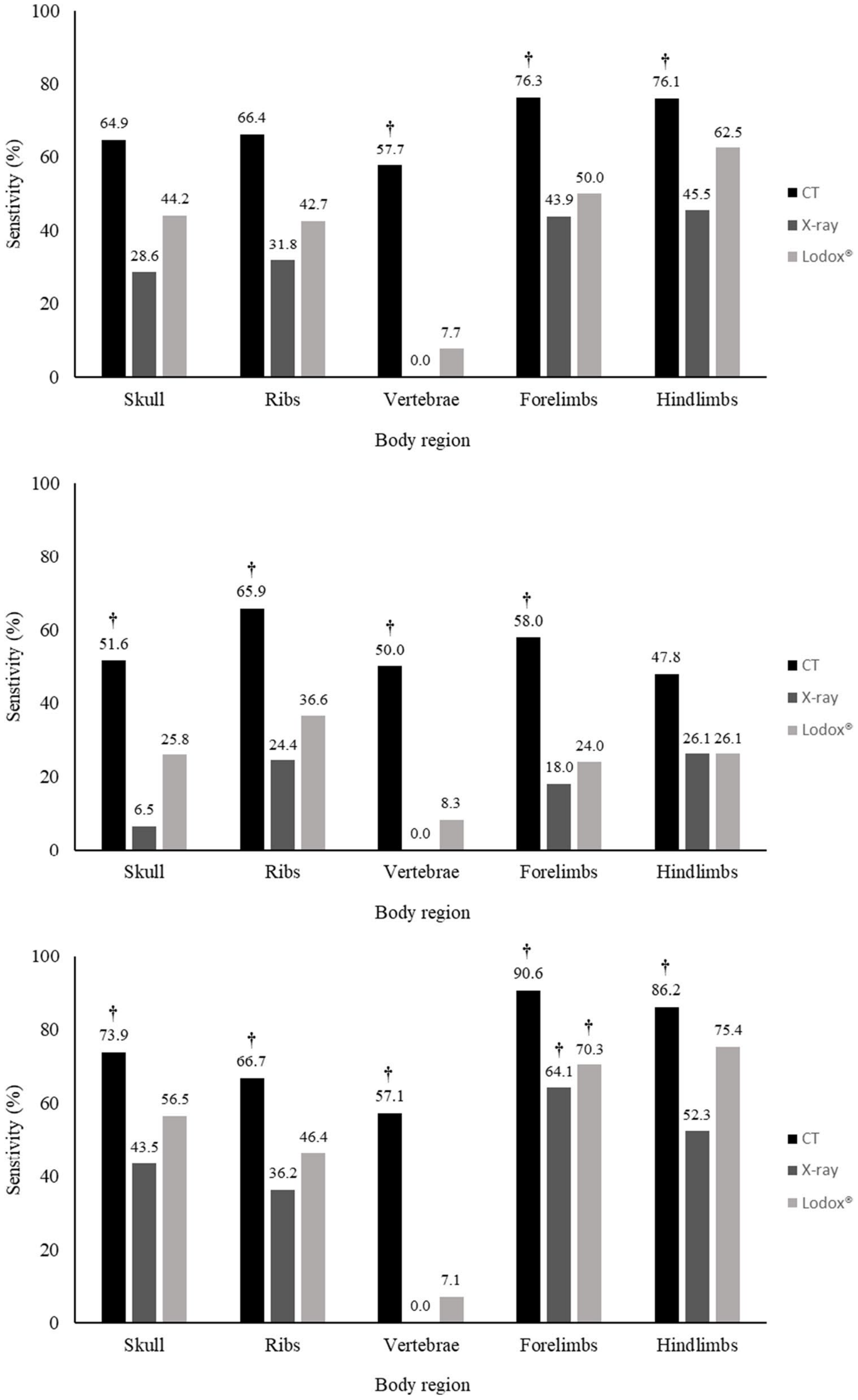

Fig. 8 Sensitivities of CT, X-ray, and Lodox scans for detecting all sharp force defects (top), stab wounds (middle), and chop marks (bottom) in each body region. †No significant difference from the dry bone results ($p > 0.01$)

When compared to the detection of cranial fractures as a result of BFT (CT 51.4%; X-ray, 10.1%; Lodox, 13.8%) [33], sensitivities for detecting sharp force cranial defects in the present study are much higher. However, sensitivities for mandibular defects are much lower than those reported for BFT (CT 88.0%; X-ray, 56.0%; Lodox, 60.0%) [33]. While sensitivities for detecting cranial defects in the present study are higher than for mandibular defects using all imaging methods, the opposite is true for analyses of BFT [33].

CTs are moderately sensitive for detecting sharp force defects of the skull and should therefore be the preferred method for imaging of this region. Lodox is more sensitive than X-ray for skull defects and as a result, when a CT scan of the skull is not an option, Lodox should be used for imaging of this region.

Low sensitivities for skull defects, as is the case with X-ray and Lodox, are concerning since during incidences of violent crime, the head is the most common target for attackers and may be the only region with evidence of trauma [39]. Furthermore, sharp weapons, especially those such as knives during incidences of stabbing, may not penetrate the skull and injure the brain [40], and in the absence of any other soft tissue injury, skeletal trauma may be the only evidence of SFT.

Sensitivities for rib defects using CTs (66.4%) and X-rays (31.8%) are lower than those reported for BFT analyses, which have sensitivities of 69.3% for CTs and 37.2% for X-rays [33]. Sensitivities using Lodox, however, are comparable for SFT and BFT (42.7% and 43.3%, respectively) [33]. All imaging methods are most sensitive for identifying defects of the rib shaft, similar to what was the case for BFT [33]. Sensitivities for BFT, however, are higher using all imaging methods for all rib locations [33], except the sternal end using X-rays and Lodox, for which sensitivities are higher when detecting SFT. All imaging methods have much higher sensitivities for detecting chop marks to the ribs compared to stab wounds (Fig. 8), likely because chop defects are much larger and result in more bone trauma and deformation and are therefore easier to detect (Fig. 2). These results indicate that CTs should be used for imaging of the rib cage since sharp force defects are less likely to be missed, and injury to the underlying organs and vasculature can be sought during clinical examinations or included as possible causes of death during post-mortem investigations. In the absence of a CT scanner, a Lodox scan should be taken to detect SFT to the chest.

When considering the vertebrae, X-rays are completely insensitive, not detecting any vertebral defects, and Lodox are only slightly more sensitive, detecting 7.7% of all defects. Sensitivities using CTs and Lodox in the present study are higher than those reported for BFT examinations (CTs 20.8%; Lodox 0.0%), while sensitivities using X-rays are the same (0.0%) [33]. The sensitivity for chop marks using CTs was higher than for stab wounds, but Lodox was slightly more sensitive for stab defects. This may be because many of the chop marks involved the transverse processes, which are highly superimposed in Lodox scans and therefore difficult to detect. The vertebral column is the region for which all imaging modalities are least sensitive for detecting sharp force defects, which is alarming since SFT to the vertebrae may be associated with injury to the spinal cord [41], and SFT particularly to the cervical vertebrae may be an indication of a slit throat or decapitation [2, 6, 42, 43], critical information to have during clinical and forensic investigations.

For both the fore- and hindlimbs, most sharp force defects (both stab and chop defects) were detected using CTs, while the least were identified using X-rays (Fig. 8). Forelimb sensitivities are comparable to those for BFT fracture detection using X-rays (43.3%) and Lodox (50.0%), but higher for SFT defects using CTs (76.3%), which is 70.0% for BFT fractures [33]. For the hindlimbs, sensitivities for CTs and Lodox are higher for SFT defects compared to BFT fractures (63.6% using CTs and 47.7% using Lodox), but lower using X-rays (52.3% for BFT) [33]. The limbs are the regions with the highest overall sensitivities using all imaging methods, likely because superimposition in these regions is limited and trauma is therefore easier to detect. This is also true when chop marks as a result of hacking trauma are considered (Figs. 5 and 7). However, when defects as a result of stabbing trauma are considered, sensitivities are low to moderate. In fact, sensitivities for the hindlimbs using CTs are lower than all other regions for detecting stab wounds. This may be because stabbing trauma to the limbs, because of their sturdy nature, often result in puncture defects or small cut marks which are difficult to detect (Figs. 4 and 6), while stab wounds of the ribs, for example, more often result in hinge fractures which are easily identifiable (Fig. 2). Sensitivities for detecting stab defects to the limbs using CTs is still, however, considered moderate. The moderate to high sensitivities for detecting limb defects using CTs, and the moderate sensitivities using X-rays and Lodox, are significant since SFT to the limbs is often associated with defensive wounds [44] and can also be indicative of attempted dismemberment [6, 42, 43], information which aids in determining the circumstances surrounding the traumatic event.

Specificities are high for all body regions using all radiological tools, indicating that the likelihood of making a false-positive identification in cases of SFT is low for all methods. However, PPVs and NPVs are much more variable, and therefore, the probability of a radiologically identified defect truly being a defect is variable, as is the probability that a bone not considered to have trauma radiologically is indeed trauma-free. These results are similar to those reported for BFT analyses [33].

CTs are highly sensitive for estimating the minimum number of impacts, while X-rays and Lodox are moderately sensitive. This is similar to what was found for BFT [33]. CTs should therefore be the preferred method for estimating the minimum number of impacts inflicted during a traumatic event involving SFT.

Overall, in this study, CTs were found to be more sensitive than both X-rays and Lodox in detecting both stab wounds and chop marks in all body regions, likely because the challenge of superimposition is overcome when using CT scans, as the bones can be viewed 3-dimensionally. Therefore, when radiological imaging is needed to examine skeletal defects as a result of SFT, CTs should be the method of choice. Lodox scans are more sensitive than X-rays and should be used for the purpose of conducting radiological analyses of skeletal SFT when a CT scan is not available or in very time-sensitive instances, as it only takes approximately 13 s to generate a Lodox scan [28]. It is possible that in some cases of X-rays, the ribs or limbs were oriented or positioned in a way that may have obscured the trauma. This is likely to be less of an issue when imaging humans, where radiographers trained in forensic imaging would perform standard X-ray views on more familiar subjects, and sensitivities are therefore expected to increase slightly. Best results, however, are still achieved from dry bone analyses which should therefore be performed whenever possible.

In general, sensitivities achieved in the present study for detecting SFT are higher than those for detecting BFT [33]. There are a few potential reasons for this. SFT such as hacking trauma often results in complete bone discontinuities or bisections which are much easier to detect in comparison to hairline or incomplete fractures which are often the result of BFT. In addition, soft tissue lesions as a result of the SFT, which are visible radiologically, may help to locate sites of bone trauma (Figs. 2 and 5), which is not the case in analyses of BFT. Sensitivities for detecting SFT may therefore decrease when remains are partially fleshed, decomposed or charred. However, while soft tissue lesions may aid in locating and detecting true-positive skeletal defects, they may also result in a higher incidence of false-negative and false-positive identifications, as soft tissue injury may obscure underlying bone trauma (Fig. 4) or may be mistaken for skeletal trauma when in fact only the soft tissue is injured (Fig. 2). It is possible that a lack of soft tissue may therefore in fact improve results. Further research involving partially fleshed, decomposed, or charred remains is therefore needed.

A potential limitation of this study is that, even though the side of the body on which each weapon was used to inflict the trauma was alternated, stabbing trauma was constrained to a single side of the body and hacking trauma to the other within each individual pig. Therefore, a chop mark identified, for example, on the right ulna would introduce some bias as the observer would know that, for that specific pig, trauma to the right side of the body in all other body regions was also the result of hacking. This could be overcome by inflicting stabbing and hacking trauma randomly to each pig, independent of the side of the body.

Conclusion

Injuries as a result of SFT are common during incidences of violent crime, and a thorough examination of these injuries is critical for the proper clinical and forensic investigation of these cases. This study found CTs to be most sensitive in both the detection and macroscopic interpretation of skeletal defects as a result of SFT. Therefore, when a radiological analysis of SFT is needed, the authors suggest that this be conducted using CT scans. When such scanners are not available, virtual SFT examinations should be performed using Lodox scans, while conventional X-rays should only be used as a last resort. However, best results are still achieved when performing an osteological analysis of the remains and should therefore be the method of choice whenever possible, feasible, or practical. A macroscopic interpretation of the trauma in order to determine the type of SFT, and as a result, the class of weapon used, is possible using all imaging modalities, but caution should be used when interpreting stabbing trauma using Lodox scans. However, as Lodox may be used to detect trauma with moderate sensitivity, a CT scan or osteological analysis of the affected body region only can be performed for a more thorough interpretation of the trauma.

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Data availability Available upon request.

Declarations

Ethics approval Permission was obtained from the Animal Research Ethics Committee (AREC) at the University of the Witwatersrand (Ethics Clearance Certificate No. 2019/04/27/O), as well as from the South African Department of Agriculture, Forestry and Fisheries (DAFF).

Consent to participate Not applicable.

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