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Detection of butterfly fractures of long bones through multi-slice computed tomography and micro-computed tomography

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ABSTRACT

Motor-vehicle accidents often result in lower limb injuries with biosseous fractures.

The present study aimed at comparing multi-slice computed tomography (MS-CT), micro-computed tomography (micro-CT) and external fractography for the analyses of experimentally produced biosseus leg fractures.

Briefly, 48 human legs amputated for medical reasons were defleshed and then experimentally fractured using a 3-point dynamic bending model (70,6 J of impact energy at the middle of the anterior surface of the tibia) producing 38 biosseous and 10 mono-osseous fractures with a total of 86 fractured bones. External fractography detected 63 (73,2%) "butterfly" fractures (24 (27,9%) complete and 39 (45,3%) incomplete), 14 (16,3%) "oblique" fractures, 6 (7,0%) "comminuted" fractures and 3 (3,5%) "transverse" fractures. Forty-three (43) of the 48 included legs displayed at least one butterfly fracture located at the tibia or fibula. MS-CT correctly detected and classified 16 complete and 20 incomplete butterfly fractures, failing to properly classify 27 fractures; 19 of these misclassifications led to an interpretative error on the trauma direction (i.e., 16 incomplete butterfly fractures classified as oblique fractures and 3 incomplete butterfly fractures classified as transverse). Micro-CT correctly detected and classified 22 complete and 37 incomplete butterfly fractures, failing to properly classify 4 fractures; two of these misclassifications led to an interpretative error on the trauma direction (i.e., two incomplete butterfly fractures classified as oblique fractures).

Although further studies evaluating a wider number of fractures and fracture patterns are required to drive any definitive conclusions, this preliminary experimental investigation showed that MS-CT and micro-CT represent useful tools for reconstructing the morphology of leg fractures and could be crucial for trauma analysis in the forensic context. MS-CT could be used as a screening tool, micro-CT as second level analysis and external/internal fractography as third level, confirmatory analysis.

1. Introduction

Motor-vehicle accidents often result in lower limb injuries, which represent the most common sites of primary impacts in pedestrian victims, resulting in abrasions, bruises, lacerations and fractures, especially biosseous fractures of the tibia and fibula.

A very useful type of fracture pattern for forensic pathologists is the so-called "butterfly fracture", characterized by two oblique fracture lines meeting to create a large triangular or wedge-shaped fragment with both sides of the wedge concave [1].

This type of fracture pattern was first described in 1880 by Messerer, after conducting experiments on human long bones and, since 1885, the analysis of its morphological characteristics has been applied in forensic examinations [2,3]. These fractures are described as a result of the bending of a long bone caused by a blunt force impact that produces a combination of compressive and tensile forces along the bone shaft [4].

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Because bones are weaker in tension than compression, a transverse fracture is initially produced on the non-impact side of the bone at the point of greatest tensile stress, followed by oblique fractures on the impact side of the bone, on which a compression stress is applied, thus creating a Y-shaped fracture, with the presence of the butterfly fragment on the side of impact. Based on these findings, the orientation of the resulting wedge fragment can indicate the direction of the impact force [4,5]. However, further studies suggest that different patterns of fracture may originate from the application of equivalent impact forces.

The current gold standard technique for fracture analysis is fractography [5–8], which consists of observing the fracture surfaces (both externally and internally) with the naked eye or at low magnification after maceration and complete removal of soft tissues from the bone. To the best of our knowledge, there is a lack of studies regarding the evaluation of fractures, and, in particular, of the butterfly pattern, using radiological techniques for forensic purposes.

Therefore, the present study aims at comparing results obtained from radiology and external fractography of fractures experimentally produced on human legs, in order to assess the potential utility of high-resolution tomographic techniques for the detection of tibial and fibular butterfly fractures, discussing limits and points of strength of multislice computed tomography (MS-CT) and micro computed tomography (micro-CT) investigations.

2. Material and methods

2.1. Sample collection

The sample consisted of human legs amputated for therapeutic reasons and donated to the University-Hospitals of Bologna and Padua for research purposes maintaining donor anonimity, according to the rules of the local Ethical Committees.

The samples were CT-scanned (MS-CT 128 slices; Siemens Somatom Definition AS, Siemens Healthcare, Erlangen, Germany) in order to detect findings corresponding to the following inclusion (a, b) and exclusion (c, d, e) criteria:

a) leg amputation performed at the distal third of the femur;
b) ligamentous integrity of the tibiofemoral, tibiofibular and tibiotarsal joints;
c) fractures of the tibia and/or fibula;
d) presence of osteosynthesis devices (*e.g.*, nails, plats and screws, external fixation, etc.);
e) presence of conditions potentially affecting bone susceptibility to fracture (*e.g.*, osteoporosis, Paget's disease, neoplastic disease, etc.).

2.2. Sample preparation and experimental trials

Each selected sample was numbered, kept in plastic bags and frozen at –15 °C until the day before the experiment, when the samples were defrosted in open air for 24 h.

Three-point bending experiments were conducted in order to simulate a perpendicular impact on the leg of a standing subject. The experiment was performed using a standardized 3-point bending fixture consisting of a support structure, an impact device and a leg stand. The support structure included a base, 10 kg in weight, with a central hole that allows the insertion of a graduated longitudinal bar, 120 cm in height. The impact device consisted of a disc, 5 kg in weight, and a J-shaped bar, 1 kg in weight, fixed to each other by a metal vice. The disc had a central hole which allowed its insertion into the longitudinal bar; the short part of the J-shaped bar formed the impact surface. The leg stand consisted of two concrete blocks, which were located on both sides of the support structure.

Each sample was installed as a bridge on the leg stand, settled so that the midpoint of the leg was in the trajectory of the impact device, and fixed to the blocks with two cable ties. The impact device was placed at 1 m height on the longitudinal bar and suddenly released by an operator, resulting in a 70,6 J energy of impact. The force was applied on the anterior or posterior or medial or lateral surface of the leg, perpendicularly to the longitudinal axis of the bone (Fig. 1). Each impact experiment was recorded in slow motion (240 frames per second) using an iPad Pro (Cupertino) equipped with an ultra-wide camera.

2.3. MS-CT analysis

Following impact, the fractured legs were CT-scanned. The osiryx DICOM viewer was used to elaborate 3D volumetric reconstructions.

2.4. Micro-CT analysis

Each leg was accurately defleshed; skin and muscles were removed with a surgical scalpel without damaging the surface of the bone. Subsequently, the bone segments affected by the fracture were isolated by means of an oscillating saw, cutting the intact bone a few centimetres proximal and distal to the fracture site.

All samples were scanned with a high-resolution micro-CT 1275 (Skyscan, Bruker, Kontich, Belgium) applying the following parameters: 15.7 μm isotropic voxel size, 83 Kv, 120 μA of current, 6050 ms exposition time, 0.7 rotation step, 2 frame averaging, and 1280 x 1024 pixels Field of View. Each sample was scanned on its outer surface. The CTVox software V3.3.1 (Bruker, Kontich, Belgium) was used to elaborate 3D volumetric reconstructions.

2.5. External fractography

Following micro-CT analysis, any residual soft tissue was removed by a 21-day cold water maceration period. Each sample was afterwards examined on the outer surface of the fracture by macroscopic visual fractography with a stereomicroscope Andonstar ADSM301 (Shenzhen Andonstar Tech Co. Ltd, Guangdong, China).

The Microscope Measure software V3.6.1 (Shenzhen Andonstar Tech Co. Ltd, Guangdong, China) was used to acquire 2D images.

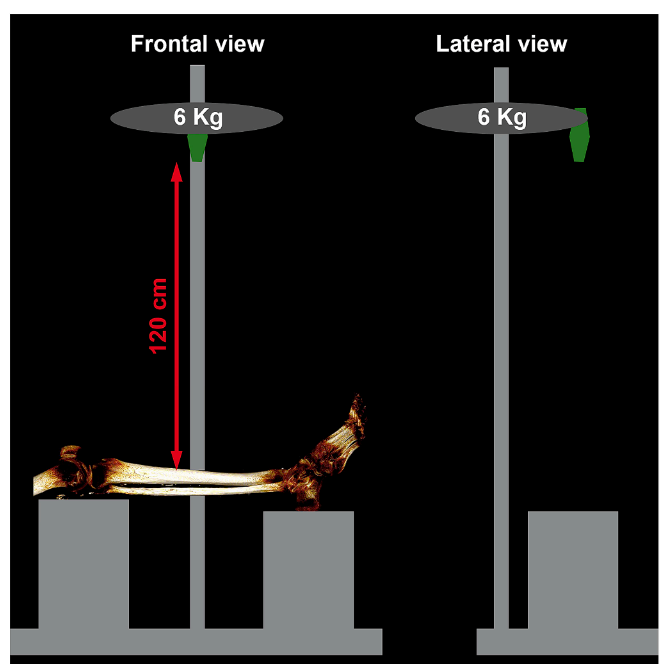

Fig. 1. Sketch of the fixture used for the leg crash tests. Briefly, the fixture consisted of a support structure, an impact device and two concrete blocks forming a leg stand. The support structure included a rigid longitudinal steel bar, 150 cm in height; the impact device weighed 6 kg.

2.6. Fracture morphology diagnosis

The outer surface of all samples was assessed in both macroscopic visual fractography and in 3D volumetric reconstructions. According to the classification of Dettmeyer et al. [9] (Fig. 2), the morphology of the external fracture surface was described as follows:

- *transverse fracture*, defined as a fracture running approximately perpendicularly to the long axis of the bone;
- *oblique fracture*, defined as a fracture running diagonally across the long axis of the bone;
- *comminuted fracture*, defined as a fracture dividing the bone into more than two fragments;
- *butterfly fracture*, a particular type of comminuted fracture consisting of two oblique fracture lines meeting to create a large triangular or wedge-shaped fragment with both sides of the wedge concave.

Moreover, butterfly fractures were classified as "*complete*" (triangular-shaped fragment bounded by fracture lines that include the entire cortical bone) or "*incomplete/partial*" (triangular-shaped fragment bounded by fracture lines that do not include the entire cortical bone).

3. Results

3.1. Study sample and fracture production

Following the adopted inclusion and exclusion criteria, 48 amputated human legs were selected and randomly impacted on the anterior (12), posterior (12), medial (12) or lateral (12) surface at their diaphyses midpoint.

The leg crash test three-point bending device produced 38 biosseous and 10 mono-osseous fractures with a total of 86 fractured bones.

3.2. External fractography

External fractography, adopted as "gold standard", detected 63 butterfly fractures (73,2%), of which 24 (27,9%) complete and 39 (45,3%) incomplete fractures. The other detected fractures were "oblique" (14; 16,3%), "comminuted" (6; 7,0%), and "transverse" (3; 3,5%) fractures (Table 1). Forty-three (43) of the 48 included legs displayed at least one butterfly fracture located at the tibia or fibula (89,6% of the

Table 1
Classification of fracture types.

External Fractography		MS-CT		Micro-CT	
Tibia	Fibula	Tibia	Fibula	Tibia	Fibula
BC: 12	BC: 12	BC: 9	BC: 7	BC: 11	BC: 11
BI: 20	BI: 19	BI: 20	BI: 8	BI: 21	BI: 18
O: 9	O: 5	O: 12	O: 19	O: 9	O: 7
T: 1	T: 2	T: 1	T: 6	T: 1	T: 3
C: 3	C: 3	C: 3	C: 1	C: 3	C: 2
NF: 3	NF: 7	NF: 3	NF: 7	NF: 3	NF: 7
Total		***Total***		***Total***	
BC: 24		BC: 16		BC: 22	
BI: 39		BI: 28		BI: 39	
O: 14		O: 31		O: 16	
T: 3		T: 7		T: 4	
C: 6		C: 4		C: 5	
NF: 10		NF: 10		NF: 10	
Gold standard		***Diagnostic errors***		***Diagnostic errors***	
		8 BC –> BI		2 BC –> BI	
		16 BI –> O		2 BI –> O	
		3 BI –> T		1 C –> T	
		1 C –> T			
		1 C –> O			

BC: Complete butterfly fracture
BI: Incomplete butterfly fracture
O: Oblique
T: Transverse
C: Comminuted
NF: Not Fractured

Table 2
Number and distribution of butterfly fractures.

	Whole leg		
	Fractography	MS-CT	Micro-CT
Number of butterfly fractures	63	44	61
Number of legs affected by butterfly fractures	0/2:5 1/2:23 2/2:20	0/2:14 1/2:24 2/2:10	0/2:5 1/2:25 2/2:18

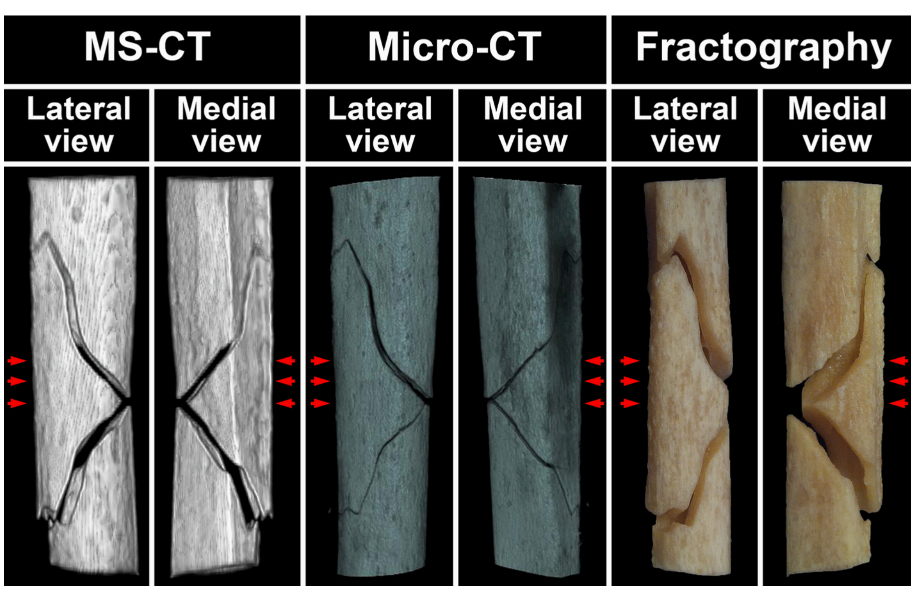

Fig. 2. Different boxes displaying the medial and lateral views of a fibula All the applied techniques/methods show a complete butterfly fracture. The red arrows indicate the direction of the impact.

included legs with at least one butterfly fracture) (Table 2).

3.3. MS-CT analysis

MS-CT correctly detected and classified 16 complete (Fig. 2) and 20 incomplete butterfly fractures, failing to properly classify 27 butterfly fractures; 19 of these misclassifications led to an interpretative error pertaining the trauma direction (i.e., 16 incomplete butterfly fractures classified as oblique fractures (Fig. 3) and 3 incomplete butterfly fractures classified as transverse) (Table 1).

3.4. Micro-CT analysis

Micro-CT correctly detected and classified 22 complete (Fig. 2) and 37 incomplete butterfly fractures (detection rate of 93,5% compared to fractography), failing to properly classify 4 butterfly fractures; two of these misclassifications led to an interpretative error pertaining the trauma direction (i.e., two incomplete butterfly fractures classified as oblique fractures) (Table 1).

3.5. Trauma reconstruction

Considering the capability of identifying the trauma direction based on the presence of at least a butterfly fracture in one bone (tibia or fibula), MS-CT allowed to detect 70,9% (34/48) of the trauma directions, whereas micro-CT allowed to detect 89,6% (43/48) of the trauma directions (Table 2).

4. Discussion

The analysis of bone injuries is of great interest for both forensic pathologists and anthropologists as they can provide useful information on the trauma and the circumstances of death [10]. The butterfly fracture pattern is described as a result of long bone bending and is commonly detected following blunt trauma of the lower legs, as in cases of motor vehicle–pedestrian collisions [11–13]. In this context, the identification of butterfly fractures might be crucial for determining the direction of the bending force and establishing the position of the victim in car-to-pedestrian collisions.

In the forensic literature, it is well-known that the fracture pattern of the long bones can vary greatly even under controlled experimental conditions and standardized impact dynamics (force, direction and point of impact) [4,5,14]. Emrith et al. [6], examining 49 fractured ovine femurs resulting from a 3-point bending impact, observed different fracture patterns, of which the butterfly fracture was the most common one (67 %). In a recent study conducted by Cohen et al. [15], a comminute “false” butterfly pattern was mostly observed in pig femoral bones subjected to lateral and anterior impacts. In the present study, a controlled 3-point bending experiment (70,6 J of energy, orthogonal direction, midpoint impact site) on human long bones produced 38 biosseous and 10 mono-osseous fractures with a total of 86 fractured bones. External fractography allowed to detect 63 (73,2%) “butterfly” fractures (24 complete, 39 incomplete), 14 (16,3%) “oblique” fractures, 6 (7,0%) “comminuted” fractures and 3 (3,5%) “transverse” fractures. Forty-three (43) of the 48 included legs displayed at least one butterfly fracture located at the tibia or fibula (89,6 % of the included legs with at least one butterfly fracture).

Regarding the type of butterfly fracture, as previously reported in the forensic literature, incomplete type represents a significant proportion of the total butterfly fractures. In light of the above, it is crucial to consider even incomplete fractures for the reconstruction of the morphology of the bone lesion.

In the present study, considering both complete and incomplete fractures, fractography showed that all the 63 experimentally produced butterfly fractures were “tension wedge” types, with the apex of the wedge located where the force was applied (i.e., direction of the trauma, in line with the Messerer’s study), and that 24/63 were “complete” butterfly fractures, whereas 39/63 were “incomplete” fractures. None of the detected butterfly fractures were “compression wedge” fractures, although this pattern has been widely described in literature.

Concerning the effectiveness of radiological techniques for the detection of bone fractures in the forensic field, several authors found that the combination of forensic autopsy and post-mortem computed tomography, particularly for the analysis of fractures of the skull, spine, clavicle, scapula, ribs and lower legs, significantly increased the number of detected fractures in comparison to conventional forensic autopsy alone [16,17]. On the other side, micro-radiology of bones and cartilages has been widely used for the evaluation of tissue morphology, microarchitecture and composition [18–20]. Baier et al. [21] examined pediatric rib injuries through micro-CT and histological analyses demonstrating that micro-CT was able to identify 69 % of the fractures detected by histology as well as an additional 22 % of fractures not identified through histology. Nonetheless, the potential role of high-resolution radiological techniques has not been thoroughly investigated for the characterization of butterfly fractures of long bones. For this reason, in the present study, fractures experimentally produced on

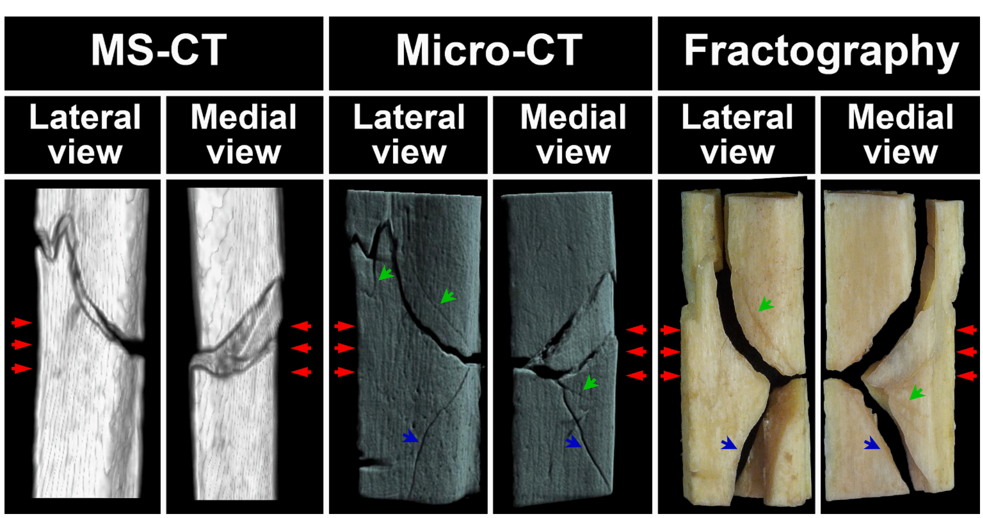

Fig. 3. Different boxes displaying the medial and lateral views of a fibula. MS-CT shows a “comminuted” fracture; micro-CT an “incomplete butterfly”; fractography detects a “complete butterfly”. The red arrows indicate the direction of the impact. Blue arrows indicate the part of the butterfly fracture classified as incomplete at micro-CT and as complete at fractography. Green arrows indicate the fractures which are incomplete both at micro-CT and fractography.

human legs were analysed through MS-CT and micro-CT, comparing radiological results to external fractography adopted as “gold standard” (i.e., MS-CT cannot analyse the internal features of a fracture).

MS-CT and micro-CT had a lower detection rate of both complete and incomplete butterfly fractures compared to external fractography. In particular, MS-CT classified as incomplete 8 complete butterfly fractures and, more importantly, classified as “oblique” or “transverse” 19 incomplete butterfly fractures. On the other side, micro-CT classified as incomplete two complete butterfly fractures and, more importantly, classified as “oblique” two incomplete butterfly fractures. Beside better sensitivity of external fractography, another possible explanation for this finding resides in the fact that MS-CT and micro-CT analyzed the samples with preserved *peri*-osseus tissues, holding together the fractured bone fragments, and thus hindering the identification of any complete fractures, even when a complete fracture rhyme was present (Fig. 3).

More importantly, considering the capability of identifying the trauma direction based on the presence of at least a butterfly fracture in one bone (tibia or fibula), MS-CT allowed to detect 70,9,% (34/48) of the trauma directions, whereas micro-CT allowed to detect 89,6% (43/48) of the trauma directions, analogous to external fractography (Table 2).

The lower sensitivity of MS-CT might be related to its lower resolution power compared to micro-CT [22,23], which allows a better morphological characterization of the fracture lines.

Notwithstanding, MS-CT did not produce any false positive results (any detected complete or incomplete butterfly fracture was confirmed by fractography) but produced false negative results. Indeed, when an “oblique” or “transverse” fracture is detected at MS-CT a second level analysis (micro-CT or fractography) is necessary because the real fracture might be an incomplete or complete butterfly fracture.

Comparing the points of strength and weakness of the two radiological techniques here employed for the forensic identification of butterfly fractures, the following issues have emerged. Micro-CT, due to its higher resolution power [24], allowed the detection of butterfly fractures with a sensitivity and selectivity comparable to those of fractography, whereas MS-CT displayed a lower diagnostic efficiency (more than 20 % of false negatives). On the other side, MS-CT is the only non-destructive technique as the whole legs can be analysed during a total-body scan of the corpse, detecting more than one fracture at a time and keeping the anatomical landmarks visible on the acquired images. Therefore, MS-CT, regardless of its sensitivity limitations, represents the most rapid, non-invasive, and non-destructive method for investigating bone injuries to the legs, applicable also to living subjects.

In the post-mortem setting, although fractography remains the gold-standard, micro-CT showed promising results in terms of diagnostic efficiency, rapidity of analysis, and interpretability of images. Sample preparation is faster and less complicated than that for fractography (i.e., it does not require the maceration and destruction of the *peri*-osseous soft tissues, thus allowing any further histological or immunohistochemical analyses), although due to the small size of the micro-CT sample chamber (96 mm diameter, 120 mm height), the bone must be sawn, and the fractured segment must be isolated from the non-fractured bone for the radiological acquisition. If the fractured sample is too huge (*e.g.*, epiphysis of the tibia) micro-CT analysis might be impracticable.

Obviously, there are several limitations affecting the proposed experimental study.

Firstly, this study focused on fractures experimentally produced using a 3-point bending experiment, not reproducing all the potential types of blunt impact occurring in a real pedestrian-to-car accident.

Secondly, fractures were produced on defleshed bones, without skin and clothes; therefore, the experimental model here used is not perfectly adherent to a real forensic setting. The presence of clothes and soft tissues could have reduced the impact force applied to the bones, although, due to the anatomical conformation of tibia and fibula, no relevant differences would have probably been observed in this particular type of anterior trauma to the leg.

Thirdly, a limited number of specimens was included in the study and general information about donors (i.e. age, sex, medical history) was not assessable due to the anonymization of the amputated legs.

Finally, different fracture patterns might have been produced using 4-point bending methods [5] and/or changing the impact characteristics (i.e., direction, force, point of impact).

5. Conclusions

Although further studies evaluating a wider number of fractures and fracture patterns are required to drive any definitive conclusions, this preliminary experimental investigation showed that radiological techniques (in particular, MS-CT and micro-CT) represent useful tools for reconstructing the morphology of leg fractures and could be crucial for trauma analysis in the forensic context. Basing on these preliminary results and considering the advantages and limitations of MS-CT and micro-CT investigations, an integrated approach could be proposed for the analysis of leg fractures in trauma-related deaths.

In the future, in cases of motor vehicle–pedestrian incidents, specific protocols could be elaborated, using MS-CT as a screening tool to reveal the main fracture patterns of the long bones, as well as other traumatic injuries. Instead, micro-CT could be considered as a second level analysis useful for characterizing those fractures classified as “transverse” or “oblique” at MS-CT and that could hinder an incomplete or complete butterfly fracture. Subsequently, in cases of doubtful micro-CT images, external and internal fractography could be used as confirmatory third level analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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