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Blunt Force Trauma Analysis: Reconstruction of the circumstances of injury using multi-criteria approach

Tese no âmbito do Doutoramento em Antropologia, Antropologia Forense, orientada pelos Professores Eugénia Maria Guedes Pinto Antunes da Cunha, e Pascal François Jérôme Adalian e apresentada ao Departamento de Ciências da Vida da Faculdade de Ciências e Tecnologia da Universidade de Coimbra

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To my parents

"Choose a job you love, and you will never have to work a day in your life"

Confucius

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Abstract

One of the primary roles of forensic anthropologists is to analyze and interpret bone trauma; they essentially give an expert opinion on the circumstances surrounding an individual's death by explaining the mechanism of trauma from a skeletal fracture.

In Blunt Force Trauma (BFT) analysis, an important dilemma remains the diagnosis of lesions caused by falls or blows.

This study aimed to strengthen the forensic evidence for analyzing and interpreting skeletal BFT resulting from falls and blows.

To address this aim, documented cases of falls and blows were examined to investigate if there were fracture patterns and morphologies characteristic of these types of trauma circumstances. Skeletal trauma was examined from hospital cases from Marseille (France), Nancy (France), and Coimbra (Portugal). For falls (n = 265) and blows (n = 165), retrospective polytrauma computed tomography scans were reviewed for skeletal trauma. The details of each etiology were recorded from the associated medical report. Details comprised intrinsic variables (i.e., age and sex) of both etiologies. Fracture patterns and morphologies were examined with logistic regression, multivariate statistics (the mean measure of divergence), and a supervised learning method used for classification (decision tree).

Findings indicate many significant fracture patterns and morphologies characteristic of each etiology.

A new methodology was proposed based on four prediction models thanks to the use of random forest. The classification is based on a binary quotation of fractures on 12 anatomical regions or 28 bones with or without baseline (age and sex). For once, a distinction between falls and blows can be proposed with fractures on the infracranial skeleton and the skull, not only with the latter.

An application with an intuitive interface and grouping of all these elements has been created and is freely available at https://grmoex.shinyapps.io/fracture/.

The results of this research improve the current understanding of the skeletal BFT and can help the forensic anthropologist interpret the mechanism of BFT in medico-legal cases where the circumstances of the death are unknown but suggest that someone else was involved.

Resumo

Um dos objetivos na perícia de Antropologia forense é analisar e interpretar os traumatismos ósseos, ajudando a explicar os mecanismos causais, de forma a esclarecer as circunstâncias que rodearam a morte do indivíduo. No caso dos traumatismos contundentes é essencial fazer o diagnóstico diferencial entre lesões causadas por quedas ou por violência interpessoal.

O presente estudo teve como objetivo aprofundar o conhecimento dessas lesões esqueléticas de forma a melhorar a performance da sua análise e consequente interpretação.

Foram analisados retrospetivamente, casos clínicos de quedas e de violência interpessoal, procurando-se padrões e os tipos de fratura característicos que permitam diferenciar as lesões esqueléticas traumáticas causadas por quedas das por violência interpessoal. Os casos, provenientes de hospitais de Marselha e Nancy (França) e Coimbra (Portugal), totalizam 265 vítimas de quedas e 165 vítimas de violência interpessoal. Além do relatório médico, onde se encontravam diversas informações como a etiologia idade e sexo da vítima, também foram analisadas tomografias computadorizadas. Os padrões e os tipos de fratura foram avaliados com recurso a regressão logística, análise multivariada (a medida média de divergência) e um método de aprendizagem supervisionado usado para classificação (árvore de decisão).

Os resultados apontam para a existência de padrões de fratura característicos de cada uma das etiologias sob estudo.

Com este estudo, propõe-se uma nova abordagem metodológica com base em quatro modelos de predição graças a um classificador *random florest*. A classificação é baseada numa cotação binária de fraturas em 12 regiões anatómicas ou 28 ossos com ou sem variáveis intrínsecas (idade e sexo). Pela primeira vez, uma distinção entre quedas e violência interpessoal, pode ser feita para fraturas do esqueleto craniano e pós-craniano em simultâneo. Foi criada uma aplicação com interface intuitiva que está disponível gratuitamente em https://grmoex.shinyapps.io/fracture/.

Ao aumentar o *corpus* documental das lesões traumáticas contundentes, espera-se que os resultados obtidos com o presente estudo melhorem as capacidades interpretativas dos antropólogos forenses em casos em que as circunstâncias da morte são desconhecidas.

List Of Abbreviations

A Absence

ABFA American Board of Forensic Anthropology

AO Arbeitsgemeinshaft für Osteosynthesefragen

AP-HM Assistance Publique-Hôpitaux de Marseille

AR Anatomical Regions

ASIF Association for the Study of the problems of Internal Fixation

BFT Blunt force trauma

CCNE National Consultative Ethics Committee for health and life sciences

CHRU Centre Hospitalier Regional et Universitaire de Nancy

CHUC Centro Hospitalar e Universitário de Coimbra

CNECV National Council of Ethics for the Life Sciences

CT Computed tomography

DICOM Digital imaging and communications in medicine

FASE, Forensic Anthropology Society of Europe

HBL Hat brim line

ISS Injury severity score

Kv Kilovoltage peak

M Multiple

Max Maximum

Min Minimum

MIP Maximum Intensity Projection

mm millimeter

MMD Mean Measure of Divergence

MPR Multiplanar Reconstructions

n number of samples

NA Non-Applicable

NIST National Institute of Standards and Technology

OR Odds ratio

OTA Orthopaedic Trauma Association

PACS Picture Archiving and Communication System

PMCT Post-mortem computed tomography

ROC Receiver Operating Characteristic

S simple

Sd Standard deviation

SWGANTH Scientific Working Group for Forensic Anthropology

USA United States of America

VR Volume rendering

WHO World Health Organization

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Chapter 1. Introduction

Chapter 1: Introduction

In 1979, forensic anthropology - according to T. D. Stewart - was defined as "that branch of physical anthropology, which, for forensic purposes, deals with the identification of more or less skeletonized remains known to be, or suspected of being, human" (Stewart, 1979). The American Board of Forensic Anthropology gives a similar definition (www.theabfa.org).
Nowadays, a more updated definition of forensic anthropology says that although it was born as a sub-discipline of biological anthropology, it is now an autonomous forensic discipline that applies and adapts some of the methodologies of biological anthropology to solve medico-legal cases. It is a forensic science that studies bodies in an advanced state of decomposition, skeletons, isolated bones, bone fragments, charred bodies and/or bones and analyzes living individuals, specifically in the context of their identification and age (Cunha & Ferreira, 2022).

Forensic anthropology became a scientific discipline in America, in the late 1930s with, among others, Krogman's works. During the first half of the 20th century, collections of human skeletal remains were created and continuously expanded. Wars presented an opportunity for forensic anthropologists to identify human remains and collect basic biological data. These events led to creation of the central identification laboratory in Hawaii and Thailand. During the second half of the 20th century, forensic anthropologists were called more frequently by the police to help them in providing information on skeletal remains (as sex, age, populational affinities, and stature) for their investigations (forensic cases). This conjoint work with law enforcement allowed the field to develop into a scientific discipline, taking the name of forensic anthropology (Burns, 2015; Dirkmaat & Cabo, 2012; Tersigni-Tarrant & Shirley, 2013). After identification, the analysis of bone traumatic injuries is the most important contribution of forensic anthropology. Although it took some time to recognize how useful forensic anthropologists could be, nowadays it might be one of the main reasons why these experts are called to the court.
During the 80s-90s, the conducted research focused mainly on developing new standards and improving methods for determining the biological profile and trauma analysis. Since its awakening, this science did not stop improving and modernizing its methods (Burns, 2015; Dirkmaat & Cabo, 2012; Passalacqua, Pilloud, & Congram, 2021).
The available methods, according to Daubert in 1993, must be testable, replicable, reliable, and scientifically valid to be used in court (Bethard & DiGangi, 2019; Christensen & Crowder,

2009; Holland & Crowder, 2019; Lesciotto, 2015). Forensic anthropologists can help reconstruct the events around the death and if a crime has been committed by differentiating between intentional or accidental injuries (Bethard & DiGangi, 2019; De Boer, Berger, & Blau, 2021). Skeletal trauma requires methodological rigor because it is the most common evidence presented in the courtroom as forensic anthropologist testimony (Bethard & DiGangi, 2019; Lesciotto, 2015).

Forensic anthropologists' role became increasingly important, not only in the courtroom. Moreover, conserving the chain of custody is very important as it records evidence from their discovery at the crime scene until their presentation in a courtroom. It must be carefully and thoroughly documented; therefore, the role of the anthropologist is not limited only to laboratory work, it must start in the field. Human skeletal remains must be analyzed in their original context, so the presence of an anthropologist in the field/crime scene is utterly recommended (Cunha & Ferreira, 2022; Dirkmaat & Cabo, 2012; Kroman, Symes, DiGangi, & Moore, 2013; Symes, L'Abbé, Chapman, Wolff, & Dirkmaat, 2012).

The development of the field has also allowed forensic anthropologists to answer questions other than the identity of the individual (i.e., postmortem interval, trauma). The scope of the field expanded even more with archaeological and taphonomic principles and methods. This development gave birth, in the 90s, to two embraced disciplines: forensic archaeology and forensic taphonomy, which aid in comprehending trauma, among other issues. All these fields allow the recreation of the events surrounding death. Forensic anthropologists are more confident in understanding time (ante-, peri- and post-mortem), the circumstance of death, and the causes and mechanisms of skeletal trauma. All these disciplines and methodological techniques provide the forensic anthropologist with a more solid working basis, new goals, and tasks such as postmortem interval, human skeletal remains identification, and trauma analysis (Dirkmaat & Cabo, 2012; Sobrinho, Seguro, Deitos, & Cunha, 2022; Symes *et al.*, 2012).

Forensic anthropologists assist forensic investigation using their knowledge of modern human skeletal variation to determine the postmortem interval estimation (time since death), the biological profile (sex, age, population affinities, and stature), and specific characters of the so-called identity factors (ante mortem trauma, prosthesis, discrete traits, among others) for everyone, to identify victims (Cunha & Pinheiro, 2023). Trauma analysis is important in forensic cases (e.g. Homicide, accident, human rights violation, humanitarian contexts, child' abuse) because it may provide valuable information (time, mechanism, and sometimes the instrument causing the injury can be established) regarding criminal violence or accidents and, as such, it can assist the pathologist in the determination of the cause, manner and circumstance of death (Baraybar & Gasior, 2006; Galloway & Wedel, 2014b; Kimmerle & Baraybar, 2008a; Rodríguez-Martín, 2006; Sobrinho *et al.*, 2022; Symes *et al.*, 2012; Tersigni-Tarrant & Shirley, 2013). Based on their analysis and studies, forensic anthropologists provide expert testimony in the courtroom.

1. Skeletal trauma analysis and interpretation in Forensic Anthropology

Trauma analysis is important in forensic cases because it may provide information and assist the pathologist in questioning the cause and manner of death due to criminal violence or accident (Byers, 2016; Kranioti, 2015; Passalacqua & Fenton, 2012).
One of the key roles of forensic anthropologist will provide in a medico-legal investigation is the analysis and interpretation of skeletal trauma; essentially, they provide an expert opinion on the circumstances surrounding an individual's death by interpreting the mechanism of trauma from the skeletal fractures (Kranioti, 2015).

In the clinical literature, trauma is defined as "injury produced in a limited area of the body by an external violent action" (Quevauvilliers *et al.*, 2009:941). In anthropological literature, "trauma refers to injury to living tissue that is caused by a force or mechanism extrinsic to the body, whether incidental or intentional" (Lovell & Grauer, 2018:335). Davidson *et al.* (2011) gave a similar definition (Davidson, Davies, & Randolph-Quinney, 2011).
Injury can be caused by acute exposure to external force (mechanical, thermal, electrical, or chemical) to a bone that exceeds its physiological tolerance and strength. (De Boer *et al.*, 2021; Griffith & Genant, 2011; Peden, Mcgee, & Sharma, 2002). Trauma can be divided into four groups: fracture (any break in the continuity of bone), dislocation (the displacement of one or more bones at the joint; in bone, it corresponds to changes in the joint surfaces after a period of approximatively 6 months), posttraumatic deformity (pseudoarthrosis, osteomyelitis, osteoarthritis, among others) and various traumatic conditions (Hall, 2023; Lovell, 2008; Lovell, 1997; Ortner, 2003; Rodríguez-Martín, 2006; Young, 2003).
Skeletal trauma is divided into three main categories: blunt-force trauma, sharp-force trauma, and high or gunshot trauma (Cattaneo, Cappella, & Cunha, 2017; De Boer *et al.*, 2021; Dirkmaat, 2012; Love & Wiersema, 2016; Symes *et al.*, 2012). Many authors present a fourth category: thermic induced trauma (Cattaneo *et al.*, 2017; Kroman & Symes, 2013; Passalacqua

& Fenton, 2012; Passalacqua & Rainwater, 2015; Scientific Working Group for Forensic Anthropology, 2011; Sobrinho *et al.*, 2022). We can also cite new categories such as blast trauma, and mixed categories of trauma/wound as "Sharp-Blunt Trauma" or "Blunt-ballistic Trauma" (Byers, 2002; Cattaneo *et al.*, 2017; Kroman & Symes, 2013; Rodríguez-Martín, 2006; Sobrinho *et al.*, 2022).

Except for a few pioneers, trauma analysis began in the late 1980s by forensic anthropologists and medical examiners such as Hugh Berryman, Steve Symes, or O.C. Smith (Passalacqua & Fenton, 2012; Symes *et al.*, 2012). Skeletal trauma analysis studies any injury that affects bone or hard tissues (cartilage, dentition) which record permanently traumatic events (Passalacqua & Rainwater, 2015).

In many cases, bones are the only remains we have, and a lack of soft tissues can be an obstacle because they provide information. That's why the help of the anthropologist may be invaluable to understanding the mechanisms of trauma, which leads or not to death (Rodríguez-Martín, 2006). The collaboration between forensic anthropologists and forensic pathologists is crucial. It is promoted by "working groups" such as the National Institute of Standards and Technology (NIST), the American Board of Forensic Anthropology (ABFA), and the Forensic Anthropology Society of Europe (FASE), among others (Tersigni-Tarrant & Shirley, 2013; Ubelaker, 2006; Wedel & Galloway, 2014). In 2011, the Scientific Working Group for Forensic Anthropology (SWGANTH) generated a guideline to describe and interpret skeletal trauma.

Many authors agree to say that the most scientific approach to trauma analysis is by combining context, environment of the burial (preservation of bone), osteology, fracture pattern, biomechanics, and other sciences (forensic pathology, radiology, computer learning) (Blau, 2017; Galloway, Wedel, & Zephro, 2014; Kroman, 2007; Kroman & Symes, 2013; Lovell, 2008; Lovell, 1997; Passalacqua & Fenton, 2012; Pinheiro, Cunha, & Symes, 2015; Rodríguez-Martín, 2006; Symes *et al.*, 2012).

The first step in trauma analysis is to assist in recovering the remains on the field and autopsy (Galloway & Wedel, 2014b).

The second is to observe and study the injury by various means (microscopy, macroscopic examination, imaging, chemistry). All these techniques bring precious information to the interpretation of trauma (Brighton & Hunt, 1991; Cattaneo *et al.*, 2017; Pechníková *et al.*, 2015; Porta *et al.*, 2016).

According to many authors, one of the best ways to record and visualize skeletal trauma is through medical imaging (Computed Tomography, MRI, among others) because it is a non-invasive technique (Blau, 2017; Dedouit *et al.*, 2014; Galloway & Wedel, 2014a, 2014b; Lovell, 2008; Ubelaker & Montaperto, 2014). It allows more accurate assessment of damage, the visualization of both inner and outer bones at macro- and microscopic levels, and can provide three-dimensional records that can be used later (Blau, 2017; Braga, 2016; Brogdon, 2005; Dedouit *et al.*, 2014; Franklin, Swift, & Flavel, 2016; Galloway & Wedel, 2014a, 2014b; Lovell, 2008; Ubelaker & Montaperto, 2014). Every defect must be described and documented in detail (location, pattern, shape, size). Then, the anthropologist attempts to determine the type of trauma and the post-trauma interval (PTI), as well as impact site, number and sequence of blows (by applying Puppe's law, for example), areas of tension and compression, and the force applied to cause the observed injury (Blau, 2017; Davidson *et al.*, 2011; Galloway, Symes, & Haglund, 1999; Galloway *et al.*, 2014; Kimmerle & Baraybar, 2008a; Komar & Buikstra, 2008; Lovell, 2008; N. C. Lovell, 1997; Symes *et al.*, 2012; Wescott, 2013).

The final step of skeletal analysis is the preparation and testimony in the courtroom (Galloway *et al.*, 2014).

2. Medical imaging

In the medical, archaeological, and forensic fields, to visualize bones at many levels, imaging techniques have been used, as they are non-invasive. Radiology and related techniques are important tools in forensic anthropology (Brown, Silver, Musgrave, & Roberts, 2011; Dedouit *et al.*, 2006; Dedouit, 2009; Dedouit *et al.*, 2016; Franklin *et al.*, 2016; Jacobsen, Bech, & Lynnerup, 2009; Stawicki *et al.*, 2008; Thali, Dirnhofer, & Vock, 2009; Ubelaker & Montaperto, 2014). There are two categories/types: ionizing (x-rays, tomography) and non-ionizing radiation (MRI, Sonography). Ionizing radiation can damage body tissues in living patients (Braga, 2016; Brogdon, 2005; Lovell, 2008).

2.1. X-Rays

Until the Roentgen's discovery of the penetrating X-ray in 1895 no means existed to examine or measure the hidden internal world of the living human body (Figure 1). X-rays are the consequence of a collision between a metal target with high-speed electrons in a specific tube called a collimator (Arrivé, 2012; Braga, 2016; Guy & Ffytche, 2005; Vermandel & Marchandise, 2009).

Figure 1: First radiography by Röntgen of his wife's hand, 12 december 1895 (Vermandel and Marchandise, 2009, p. 34)

2.2. Computed-Tomography (CT)

Tomography found its theoretical bases in 1950. In 1972, Hounsfield presented a new revolution in imaging: the computer-assisted X-ray tomographic scanner (CAT scanner), now called Computed-Tomography (CT). Tomography is based on the same principle as radiography. It carries out an image of great resolution, using an X-rays source and a set of detectors that rotate around the subject to examine the specimen. A stack of variable-thickness sliced images (a two-dimensional grid formed by pixels) is obtained, which can produce a three-dimensional representation of the specimen formed by voxels (Arrivé, 2012; Braga, 2016; Feldkamp, Goldstein, Parfitt, Jesion, & Kleerekoper, 1989; Franklin *et al.*, 2016; Griffith & Genant, 2008; Kalender, 2009). Initially, the improvement of this tool/material was restricted to the cerebral zone, used essentially to localize tumors or stroke damage within the brain (Guy & Ffytche, 2005; Vermandel & Marchandise, 2009). Its use, as a non-invasive procedure, has influenced medicine and numerous other domains such as biology, geology, archaeology, forensic or materials science. Indeed, thanks to CT, the digitized object can be examined externally and internally without damage, and the digital data can be used at any time.

The development of spiral CT in 1989 (Kalender, Seissler, Klotz, & Vock, 1990) provided enhanced cross-sectional data acquisition and better image processing software for 3D surface reconstructions. Weber and co-workers, who took part in the study group of the tyrolean iceman, invented the term "virtual anthropology" first (Weber *et al.*, 2001; Weber, 2001, 2015). They have pointed out the enormous advantages of digitized data, such as accessibility of even hidden anatomical structures, permanent availability of the virtual object, reproducibility of measurements, application of advanced methods (geometric-morphometrics), and the possibility of easy data sharing (Weber, 2015).

2.3. Postmortem Computed-Tomography (PMCT)

PMCT is the abbreviation for post-mortem tomography (Rutty *et al.*, 2013). Its first use was in 1977 to study gunshot injuries to the head (Wüllenweber, Schneider, & Grumme, 1977).

For a few years, PMCT has been used as a complement to autopsy (Blau, Ranson, & O'Donnell, 2018; Bolliger & Thali, 2015; Bolliger *et al.*, 2008; Burke, 2012; Thali *et al.*, 2009, 2009, 2002; Thali *et al.*, 2003).

In skeletal trauma analysis and forensic cases, PMCT is an unavailable tool because bones can be observed despite soft tissue (Obertová *et al.*, 2019). Skeletal trauma can be easily detected by PMCT thanks to the quality of images and be documented in their original context (useful especially in cases of comminuted fractures) (Jalalzadeh *et al.*, 2015; Obertová *et al.*, 2019; Scholing *et al.*, 2009).

Obertova *et al.* in 2019 point out that putrefaction gases can simulate a fracture in highly decomposed cadavers, especially in thin bones (Obertová *et al.*, 2019).

3. Blunt Force Trauma

Blunt Force Trauma (BFT) is a mechanism of trauma. It occurs when a slow or high loading force is applied to the tissue. It can be caused by an object (e.g. fist, hammer, baseball bat, motor vehicle), by the human body (kicks, punches), by the impact of a body with a surface (e.g. falls from height), and by compression of major vessels of the neck (e.g. hanging, manual strangulation) (Blau, 2017; Cattaneo *et al.*, 2017; Cunha & Pinheiro, 2006; Davidson *et al.*, 2011; Galloway & Wedel, 2014a; Marinho & Cardoso, 2016; Quatrehomme & Alunni, 2013; Scientific Working Group for Forensic Anthropology, 2011; Sobrinho *et al.*, 2022; Spatola, 2015; Symes *et al.*, 2012). Blunt Force Trauma is difficult to assess because there are many factors in count (variety of causes of trauma, objects, bone fractures, and the ability to endure the impact) (Davidson *et al.*, 2011; Symes *et al.*, 2012). Younger individuals are more resistant to fractures than older individuals because their skeleton presents more cartilage and organic material (which provides them with elasticity). The elderly can present degenerative diseases affecting cortical bone and the organic-mineral content of bones (Symes *et al.*, 2012). Blunt Force injuries are characterized by a clear sign of impact, linear radiating fractures, concentric fractures, plastic deformation, and delamination (Kroman & Symes, 2013; Scientific Working Group for Forensic Anthropology, 2011). Sometimes, tool marks or impressions of tools can cause a permanent imprint on bone. As such, anthropologists can determine the general class of the object used) (Christensen, Passalacqua, & Bartelink, 2014b, 2019b; Love & Wiersema, 2016; Scientific Working Group for Forensic Anthropology, 2011; Symes *et al.*, 2012). However, one must be very careful in identifying the tool because various alterations can be made by the same tool (Sobrinho *et al.*, 2022).

In addition to providing information about the type of object or surface, skeletal fractures resulting from BFT could reflect the energy and the direction of the force causing the injury (Cattaneo *et al.*, 2017; Love & Wiersema, 2016; Sobrinho *et al.*, 2022).

Fracture morphology and pattern are important because they can inform events surrounding death and the mechanism of injury (Blau, 2017; Cattaneo *et al.*, 2017; Kimmerle & Baraybar, 2008b; Love & Wiersema, 2016; Symes *et al.*, 2012).

Blunt Force Trauma to the head, especially when accompanied by a skull fracture, is commonly fatal, and it's for this reason, the skull has been a lot studied in medical and forensic sciences (Jones, 1997; Shkrum & Ramsay, 2007; Wedel & Galloway, 2014).

Many studies were attempted on one or two-part (s) of the skeleton (skull, thorax, ribs, or lower extremities) (Bartelink, 2015; Brown *et al.*, 2011; Delannoy *et al.*, 2012; Groner, 2005; Guyomarc'h *et al.*, 2010; Jacobsen *et al.*, 2009; Juarez, 2009; Kelbaugh, 2015; Kranioti, 2015; Kremer *et al.* , 2008; Kremer & Sauvageau, 2009; Liman *et al.* , 2003; Mole *et al.*, 2015; Rupani *et al.,* 2013; Sharkey *et al.*, 2011; Wiersema *et al.*, 2014) or the entire skeleton (Marinho & Cardoso, 2016; Marinho, 2013; Petaros *et al.*, 2013). It is important to consider different bones of the skeleton because their density, flexibility, and design are different (De Boer *et al.*, 2021; Delannoy *et al.*, 2012).

The study of bone fractures is of interest. It has not escaped researchers for medical, surgical, anthropological, or forensic purposes, resulting in a multiplication of classifications and work over the past 20 years (Bennett & Browner, 1994; Bernstein *et al.*, 1996; Dirschl, 2015; Fonseca *et al.*, 2018; Kazley *et al.*, 2018; P. H. Kim & Leopold, 2012; Magerl *et al.*, 1994; Maripuri *et al.*, 2008; Marsh *et al.*, 2007; Meinberg *et al.*, 2018; Müller *et al.*, 1991; Müller *et al.*, 1987; Orthopaedic Trauma Association: Open Fracture Study Group, 2010; Rasmussen *et al.*, 1993; Schipper *et al.*, 2001; Wedel & Galloway, 1999, 2014).

3.1. The principles of biomechanics

Understanding the principles of biomechanics is essential for trauma interpretation because the force applied has characteristics that can affect the skeleton in different ways. As such, it is necessary to understand the application of mechanical principles (effect of forces on a body or an object) to living tissue (Blau, 2017; Galloway & Zephro, 2014; Hall, 2012, 2023; Kroman, 2007; Kroman & Symes, 2013; Lovell, 2008; Martin *et al.*, 2015; Sobrinho *et al.*, 2022; Symes *et al.*, 2012; Ubelaker & Montaperto, 2014; Wescott, 2013; Wozniczka *et al.*, 2015).

The injuries resulting from blunt force trauma are caused by kinetic energy (KE) transfer from an object, a body impacting a blunt object, or both (Hamblen *et al.*, 2007). Energy transferred is determined by the equation KE = ½ mass × velocity^2, velocity is an important determinant of energy transfer (Greaves *et al.,* 2021).

A mechanical disturbance, the impacting force, is important in fracture creation and propagation. The forces that produce fractures or failures can be divided into three general types according to their direction: compression, tension, and shear (bone fails first in tension and then in compression). But there is also torsion, bending, and combined loading (Figure 2) (Blau, 2017; Galloway & Zephro, 2014; Hall, 2012, 2023; Kroman, 2007; Kroman & Symes, 2013; Nordin & Frankel, 2001; Özkaya & Leger, 2001; Pearson & Lieberman, 2004; Sobrinho *et al.*, 2022; Symes *et al.*, 2012).

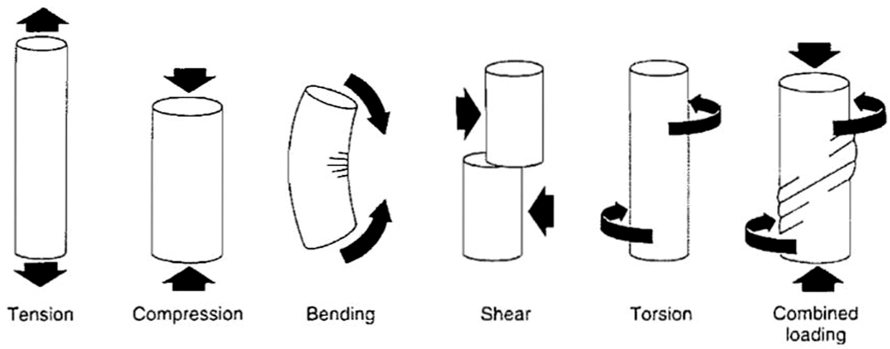

Figure 2: Types of force (Frankel & Nordin, 2001).

Biomechanics of fracture is quite complex because other parameters are also important, such as the load (weight of the object), the load type (direct, indirect, penetrating), the load rate (the speed at which the stress occurs), the direction of the load (relative to the body), the duration, the magnitude (amount of force) and the size of the object (Blau, 2017; Di Maio & Di Maio, 2001; Kroman, 2007; Molina & DiMaio, 2021; Nordin & Frankel, 2001; Symes *et al.*, 2012).

Bones change in response to their mechanical environment needs; stress and strain are the two most important parameters. Force generates stresses which produce strains. The following definitions are after Wozniczka and colleagues (2015), Zephro and Galloway (2014), Ubelaker and Montaperto (2014), Kroman (2007), Hall (2012), Özkaya and Leger (2001), Pearson and Lieberman (2004), Symes and colleagues (2012), Frankel and Nordin, (2001) and Wescott, (2013).

Stress is the force applied per unit of area. Two bones of different sizes may be loaded with the same force, but the smaller bone will fail before the larger bone because it has a smaller area. Strain is the deformation of bone in length or volume. Strain is related to stress and mechanical properties of the material (elasticity). It can be tensile (positive elongation) or compressive (negative elongation), depending upon the direction of the force. The strain will be more important for small objects for the same displacement.

Bone is an anisotropic structure. It responds differently to load according to its direction and its impact location. A loaded bone begins to deform; when the stress is released, it will return to its initial state. However, suppose the load continues and exceeds a certain point (yield point), plastic deformation occurs, and the bone will not recover its initial state when unstressed, leading it to break instead (failure point). A fracture occurs when the force applied exceeds the bone's resistance power (Cattaneo *et al.*, 2017; A Galloway & Zephro, 2014). To determine the mechanical behavior of bone (its elasticity), the modulus of elasticity (Young's modulus) is an important parameter because it represents the relationship between stress and strain (Figure 3) (Blau, 2017; Galloway & Zephro, 2014; Quatrehomme & Alunni, 2013; Symes *et al.*, 2012; Wescott, 2013).

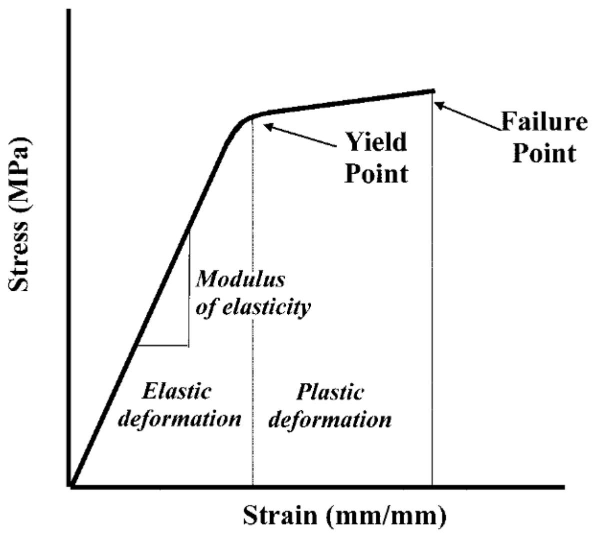

Figure 3: Graphic representation illustrating the principles of load and strain curves (Young's modulus) (Zephro and Galloway, 2014: 35).

The bone's response to a force is complex because many factors interfere:

- Extrinsic factors, such as modes of strain (compression, tension, among others), mechanism of injury, duration and repetition of strain events, the rate of strain, size and shape of the object, environmental factors (e.g., heat or humidity), velocity, magnitude and direction of applied forces (Blau, 2017; Galloway & Wedel, 2014b; Groner, 2005; Kroman & Symes, 2013; Lovell, 1997; Özkaya & Leger, 2001; Pearson & Lieberman, 2004; Rodríguez-Martín, 2006; Symes *et al.*, 2012; Tortora & Derrickson, 2020; Zimmermann *et al.*, 2015).

- Intrinsic factors, such as degree of mineralization and organization of the tissue (porosity, density, orientation of collagen fibers), age, sex, abnormal bone weakening (e.g., osteoporosis, vitamin D deficiency, Paget's disease, infection, tumor).

Immediately after injury, healing begins with an inflammation phase (characterized by the development of a hematoma), followed by a reparative phase (soft callus), and finally, a remodeling phase (hard callus) (Delahay & Sauer, 2007; Symes *et al.*, 2012).

3.2. Types of fractures

The skeletal pattern of fractures is important because it may help to clarify the probable causes of trauma. Fracture patterns can result from a specific series of events (falls, road traffic accidents, direct blow on the bone, electric shock, blast) and can be representative of the type of trauma (Christensen *et al*., 2014a, 2019a; Galloway & Wedel, 2014b; Guyomarc'h *et al.*, 2010; Marinho & Cardoso, 2016; Tersigni-Tarrant, 2015; Willits, *et al*., 2015). However, confusion in interpretation can take place. As Rodríguez-Martín (2006) claims "different lesions may be caused by the same method, and several methods may produce the same lesion" (Lovell, 1997; Rodríguez-Martín, 2006; Spatola, 2015). According to Passalacqua and Fenton (2012), getting a better understanding of fracture patterns is necessary to use them for trauma interpretation.

Fracture patterns and their characteristics are influenced by three extrinsic variables: the applied force, the area of impact, and acceleration/deceleration (Kroman, 2007).

Their typology is reported by Alison Galloway (2014) according to skeletal involvement (entire skull, throat structures, axial skeleton, upper extremity, and lower extremity).

Fractures can be divided into two groups, incomplete and complete fractures.

To determine the possible point of fracture impact, we must recognize direct and indirect trauma, and the different types of fractures they cause. They are enumerated below according to Lovell (1997), Burke 2012, and Galloway and colleague (2014a).

3.2.1. Incomplete fractures

Incomplete fractures are fractures, which do not cause complete bone breakage (Figure 4). In other words, bone fragments are still joined. These occur more in children than in adults and when the impact force is low or dissipated (wild area of impact) (Galloway & Wedel, 2014a).

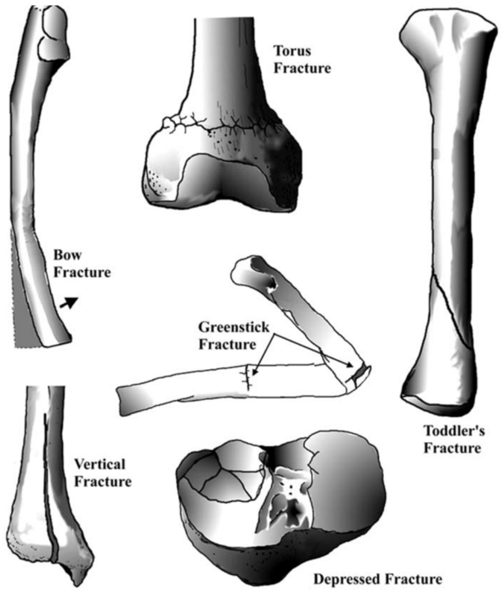

Figure 4: Classifications of incomplete fractures (Galloway, Wedel, 2014a, p.60)

A *bone bruise* is a micro-fracture caused by compression or impaction.
Plastic deformation occurs before the failure point, this type is often observed in juveniles.
Toddler's fracture is often oblique or spiral fractures of the lower limb. It occurs in toddlers and infants.
Compressive forces produce *torus fracture* and create a buckling of the bone cortex. It often occurs in children.
A *greenstick fracture* occurs more frequently in ribs and children. It is a transverse fracture and a bending of bone.
Depressed fracture involves only the outer table of the skull, or if the outer table is broken, the inner table presents incomplete fractures. This fracture often occurs in the skull and results from direct blows.
Vertical fracture is rare and occurs along the long axis of long bones.

3.2.2. Complete fracture

Complete fractures separate the bone into two (simple fracture) or more pieces (comminuted fracture) (Figure 5). There is a complete separation of the cortex circumferentially.

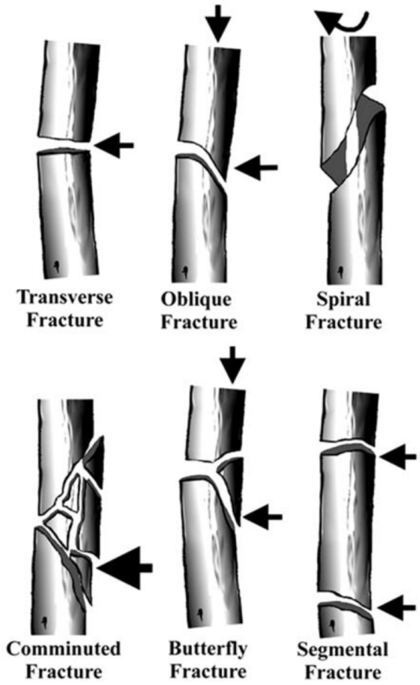

Figure 5: Classifications of complete fractures (Galloway, Wedel, 2014a, p.64)

A *transverse fracture* is a fracture that occurs approximately at right angles to the long axis of the bone.

An *oblique fracture* occurs diagonally across the diaphysis.

A helical break that spirals around the bone's long axis distinguishes a *spiral fracture*.

A *comminuted fracture* is a bone broken into more than two fragments.

An *epiphyseal fracture* occurs when the presence of a cartilaginous growth plate is present between the diaphysis and the epiphysis. The fracture may be limited to the cartilaginous growth plate but can extend to the epiphysis.

3.2.3. Direct trauma

Direct trauma results from bone breakage at the point of impact and may produce the general types of fractures below.

Tapping fractures occur when a small force is applied to a small area of bone (transverse fracture or sometimes oblique fracture).

Crush fractures occur when a large force is applied to a large area of cancellous bone. This force produces a depression fracture if applied only to one side of the bone or a compression fracture if applied to both sides.

3.2.4. Indirect trauma

An indirect fracture propagates toward and away from the point of impact. There are different types described below.

Avulsion fractures occur when a proximal or distal end of a bone is torn away from the rest of the bone by tension on a ligament or tendon attachment.

Linear fractures result from a direct blow of high intensity which extends to the fractures at the point of impact.

Tension fractures are avulsion fractures that occur perpendicularly to the applied force.

Angulation fractures occur when a bone is bent (transverse or shearing fractures).

Rotational fractures occur when a bone is twisted (horizontal and vertical shear forces), and small vertical cracks and spiral fractures appear.

Compression fractures in long bones resemble longitudinal and burst fractures (vertical compression, which breaks a vertebral disk, and disc tissue is forced into the vertebral body) in vertebrae.

4. Falls

The World Health Organization (WHO) defines a fall as an event where a person rests on the ground (World Health Organization, 2021). A fall may result from standing, any height, stairs or associated with violence interpersonal.

In the event of a fall, direct and indirect forces act on the body and can cause skeletal trauma. A direct force is generated from the initial impact on the landing surface, and then an indirect force is transmitted throughout the body as this initial energy dissipates.

5. Blows

We consider blows as interpersonal violence. According to the World Health Organization (WHO), violence is the intentional use of physical force against another that results injury or death; interpersonal violence is violence between individuals, within the family, or in the community (Petridou & Antonopoulos, 2017; World Health Organization, 2002).

Interpersonal violence can be divided into two sub-categories, on the one hand, the violence between family members and intimate partners, and on the other hand, violence between unrelated individuals (World Health Organization, 2002).

Interpersonal violence includes homicides and assaults, among others (Petridou *et al.*, 2002).

Blows can be done with weapons (baseball bats, rocks, pipes, among others) or without, only parts of the body (hand, feet, knee, among others) during an assault (Galloway & Wedel, 2014b; Madea *et al.*, 2022).

6. Research aims and thesis structure

In cases of skeletonized remains, the forensic anthropologist has the challenge of providing an interpretation of the mechanism from Blunt Force Trauma.

An anthropologist can provide information about the circumstances of the traumatic event in the courtroom by answering some questions:

- What are the most likely circumstances of the observed traumatic lesions?
- Is the BFT mechanism the result of a fall or a blow?
- Can these two etiologies' fracture patterns, localization, and typologies be differentiated?

Under current court admissibility guidelines, scientific evidence must meet some criteria (large sample sizes, repeatable and quantifiable methods), so experimental research is fundamental.

The differentiation between injuries caused by falls and injuries caused by blows was always based on the skull. No study has focused on parts of the skeleton as the trunk and the head simultaneously. These two parts are important because they are causes of morbidity and mortality in both young and old victims.

This study aims to investigate patterns, morphologies, and the distribution of the skeletal fractures resulting from falls and blows to improve the interpretations of skeletal BFT in forensic anthropology. This could differentiate each traumatic event and be helpful in medico-legal questions.

Are the skeletal fracture patterns, distributions, and fracture morphologies characteristic of falls or blows?

The aims and subsequent structure of this thesis are as follows:

Aim 1: to identify what is currently known of the skeletal fractures in the distinction between falls and blows (Chapter 2)

Aim 2: to develop a methodological approach using classifications of BFT fractures from clinical medicine and forensic anthropology, and contextualized data of living people (Chapter 3)

Aim 3: to investigate the fracture patterns, the number of fractures, and the localization of fractures on the skull and trunk that result from falls and blows using the methodology established in aim 1. We investigated hypotheses as follows:
In the context of the intrinsic variables (i.e., age, sex) of living individuals, are there specific fracture distributions and their numbers characteristic of falls and blows (Chapter 4.1)?
In the context of the intrinsic variables (i.e., age, sex) of living individuals, are there specific fractures morphologies and patterns of falls and blows (Chapter 4.2)?

Aim 4: to develop a methodology and software and test its validity on a forensic sample of deceased individuals (Chapter 4.3)

Aim 5: to discuss the outcomes, implications, and limitations of these findings to forensic investigations and to provide recommendations for further refinement of these findings.

Chapter 2. Review of the literature

The first author who tried distinguishing between falls and blows was Richter about the distinction of child abuse (Fracasso *et al.*, 2011; Richter, 1905a). He highlights the attention that must be paid on the number of skin bruises and their localization. If there are no special reasons for repeated falls, if the bruises are numerous and localized at regions that cannot be involved in cases of fall (the cranial vertex); we can hypothesize that the child is beaten.

According to Kratter in 1921, blows can cause injury in every region of the head with the exception of the base of the skull ; falls cannot cause injuries on region of vertex and on cranial vault (above the line that binds the frontal eminence, the parietal eminence and the external occipital protuberance) except in case of fall from height or an impact against an edge or a corner (Fracasso *et al.*, 2011; Geserick, *et al*, 2014; Richter, 1905b).

Regarding a similar line, Walcher in 1931 created the Hat Brim Line (HBL) rule which says that fall related injuries from blunt head traumas do not lie above the Hat Brim Line when this conditions are fulfilled (Fracasso *et al.*, 2011; Geserick *et al.*, 2014; Walcher, 1931):

- Standing position of the individual before falling
- Flat floor without incline or stairs
- Fall from one's height (falls from a height including from stairs are excluded; idem for blows and traffic accidents)
- Absence of intermediate obstacles
- The rule does not apply to small children

Nowadays, the HBL is defined as the area, in Frankfort horizontal plane, located between (Kremer *et al.*, 2008):

- The superior line passing through the glabella (G-line)
- The inferior line passing through the center of the external auditory meatus (EAM-line)

The use of the Hat Brim Line rule is limited. Moreover, using the Hat Brim Line rule in distinguishing falls and blows is controversial. Despite this, some studies have used this rule observing skull fractures and skin lesions.

Thus, Ehrlich and Maxeiner (2000, 2002), Kremer *et al.* (2008, 2009) and Guyomarc'h *et al.* (2010) undertook studies to distinguish between falls and blows in blunt head traumas. Ehrlich and Maxeiner (2000, 2002) studied 254 falls (203 on a flat surface, 51 downstairs) and 51 blows.

They observed that lacerations from blows occur more often (55%) above the HBL, than lacerations from falls (33%).

Kremer *et al.* (2008, 2009) focused on the localization of cranial fractures and number of lacerations. In the article of 2008, 36 falls (23 from one's own height, 13 downstairs) and 44 blows were observed. The results show that injuries from blows are more often found above HBL although this rule should be used with caution. The second article of 2009 observed 50 falls (29 from one's own height, 21 downstairs) and 64 interpersonal violence with a blunt weapon. The study confirms that injuries inflicted by blows are often situated above HBL, a laceration inside HBL is more in favor of a fall (66.7%), and a skull fracture inside HBL is found equitably in both etiologies.

Guyomarc'h *et al.* (2010) describe the number and length of lacerations on the entire skull, type of skull fractures, localization of injuries and the presence or the absence of postcranial injury on 50 cases of falls (29 from one's own height, 21 downstairs) and 63 cases of homicidal blows. The results show the strong discrimination potential between falls and blows case patterns with four criteria.

Sharkey *et al.* (2011) analyzed the shape, number, and localization of 377 head injuries in autopsy cases (129 falls, 60 blows, 97 whose cause of trauma is unknown, 91 which are not blunt force trauma). They showed that head injuries (skin lesions or skull fractures) are more frequent in blows (70%) that in falls (33%). Moreover, skull fractures are more likely to arise from falls and skin lesions are more likely to arise from blows.

The authors confirmed that HBL has to be used carefully and not as a single criterion in the distinction between falls and blows (Guyomarc'h *et al.*, 2010; Kranioti, 2015; Kremer *et al.*, 2008; Kremer & Sauvageau, 2009; Sterzik *et al.*, 2016). A perfect discrimination remains unrealistic and before can easily and accurately distinguish falls from blow, there is a lot more work to be performed. Moreover, we must be careful because some studies have a weak sample.

Chapter 3. Materials and Methods

The literature review detailed in Chapter 2 and the variation in the skeletal fractures as illustrated in Table 15 (Annex III), provided the foundation to develop a novel methodology to address the research questions and hypotheses.

Chapter 3: Materials and methods

1. Identifying the cases

1.1. Living cases

1.1.1. The data collection process for method development

To establish whether a distinction between a blow and a fall is possible, data collection focused on polytraumatic cases.

The term "polytraumatized" corresponds to a patient presenting several traumatic lesions, at least one of which is life-threatening. Imaging plays a key role in the management of these patients. In this way, the extent of the traumatic lesions is better apprehended.

CT scans of the skull, spine, abdomen, and pelvis are systematically performed regardless of the cause of the trauma.

The research focused on individuals aged between 20 and 49 years, with at least one fracture and whose context of trauma was either a fall or a blow (aggression, brawl, fight, interpersonal violence).

Cases with trepanations have been removed so that the possible fragility of the trepanned zone does not distort fracture scoring.

Individuals who have been resuscitated have been excluded, as resuscitation can result in rib and sternum fractures (Lederer *et al.*, 2004).

The scans were anonymized, and we recorded the age, sex, and etiology of each case.

We carried out a retrospective descriptive study from December 2008 to May 2019.

This first stage of the research, the review of the PACS (picture archiving and communication system) of the hospitals from Marseille, Coimbra, and Nancy, was given ethical approval from the Ethic Committee of the Faculty of Medicine from the University of Coimbra (CE-026/2019) (appendix I). Our work is a retrospective study that focused on CT scans from the care setting, and no additional/complementary examinations were performed for our research. The French system provides a patient agreement in the use of examinations which is not exclusive to this research.

There is, therefore, no obligation to have the prior agreement of an ethics committee to use the data, given that they are anonymized, that it is impossible to recognize the individual with the CT scan, and that there is no associated health data.

1.1.2. Selection of fall and blow types of the living

The total sample comprises 400 individuals.

The sample is composed of 235 falls and 165 blows. Fall cases come from the hospitals of Marseille (70.21%, n=165) and Coimbra (29.79%, n=70). Blow cases come from the three hospitals: Nancy (67.27%, n=111), Coimbra (21.82%, n=36), and Marseille (10.91%, n=18) (Figure 6).

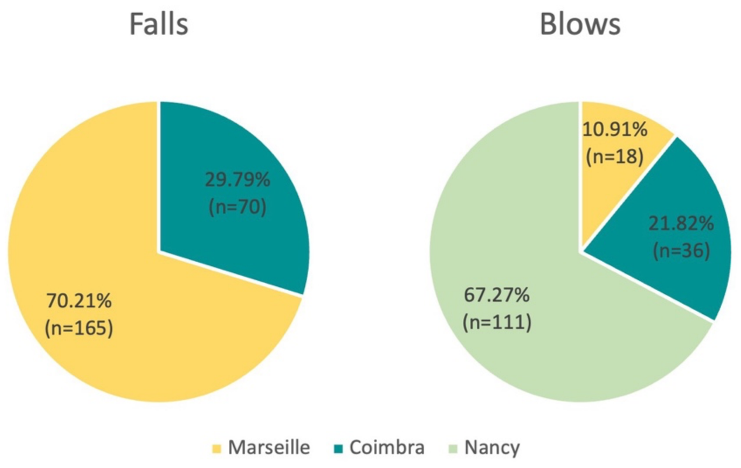

Figure 6: Composition of the sample according to their source

The sample studied consists of 58 females and 342 males aged 20-49 (Figure 7). The sex ratio (5.90) of our sample is not balanced because no selection of individuals has been made. It has been formed according to the mode of the all-coming.

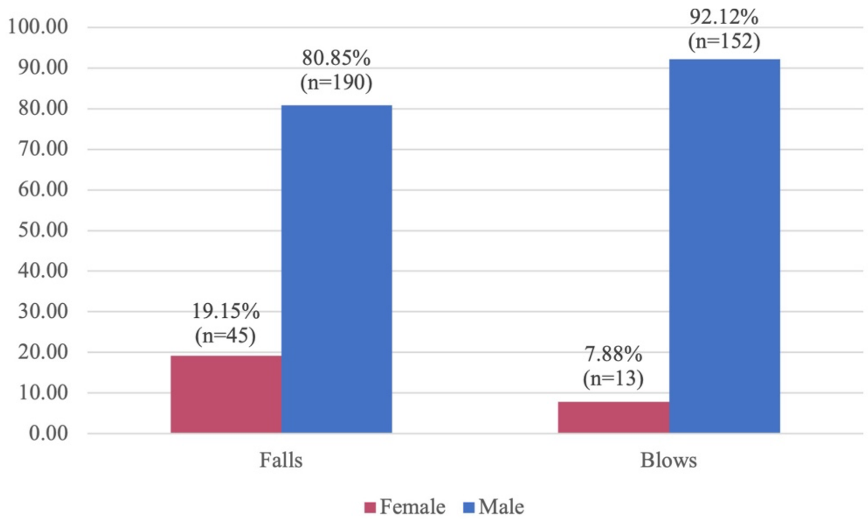

Figure 7: Distribution of the sample according to the sex

The sample is composed of 144 individuals aged 20 to 29 (36%), 120 aged 30 to 39 (30%), and 136 aged 40 to 49 (34%) (Figure 8).

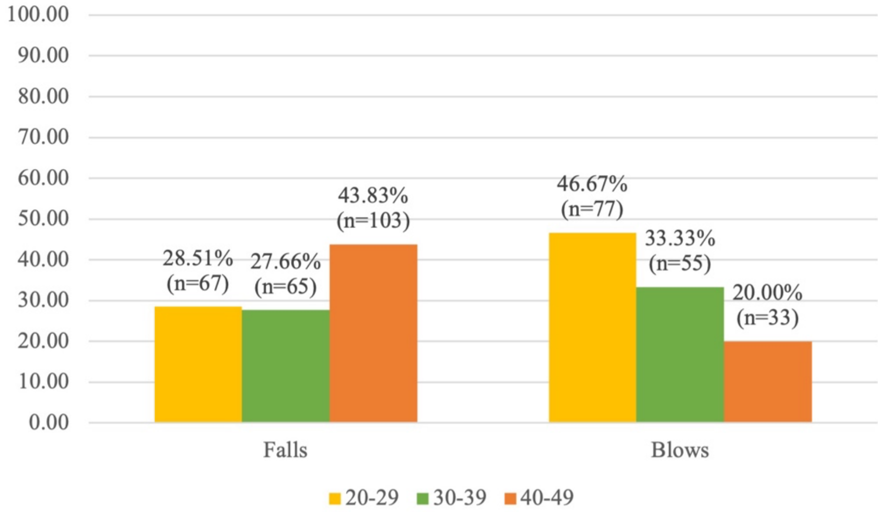

Figure 8: Distribution of the sample according to the age

The age limits have been set to avoid two types of age-dependent bias, that is:

- To have individuals whose bones are "adult", fused, thus, the osseous matrix is homogenous in the whole sample. Indeed, the plasticity of the bone is more important in the case of a nonmature individual than in an adult individual. Hence, the bone's response to the traumatic event is different. The immature individual will be more affected by plastic deformation, without counting the specific fractures to the child-like those interesting the growth cartilage.

- To avoid problems of bone degeneration that may lead to an increased risk of fracture. Bones with bone pathology are systematically excluded.

Individuals aged 20 to 29, who have undergone a CT scan following a fracture, are more involved in blows, with an occurrence of 46.67% (n=77).

In falls, individuals aged 40 to 49 are more frequent (43.83%, n=103).

Young men (20-29 years) perform most CT scans due to confused skeletal fracture etiology, hence the imbalance between age groups and the sexes (Fröhlich *et al.*, 2014).

1.1.2.1. AP-HM

The sample is composed of 183 individuals of age and sex known. The distribution by age, sex, and etiology, on which the selected skeletal trauma was scored, is presented on the histogram below (Figure 10).

The sample from the AP-HM consists of 152 men and 31 women aged 20-49; and counts more fall cases than blows (Figure 9).

The fall cases comprise 135 males (81.82%), and 30 females (18.18%).

The blow cases comprise 17 males (94.44%), and 1 female (5.56%).

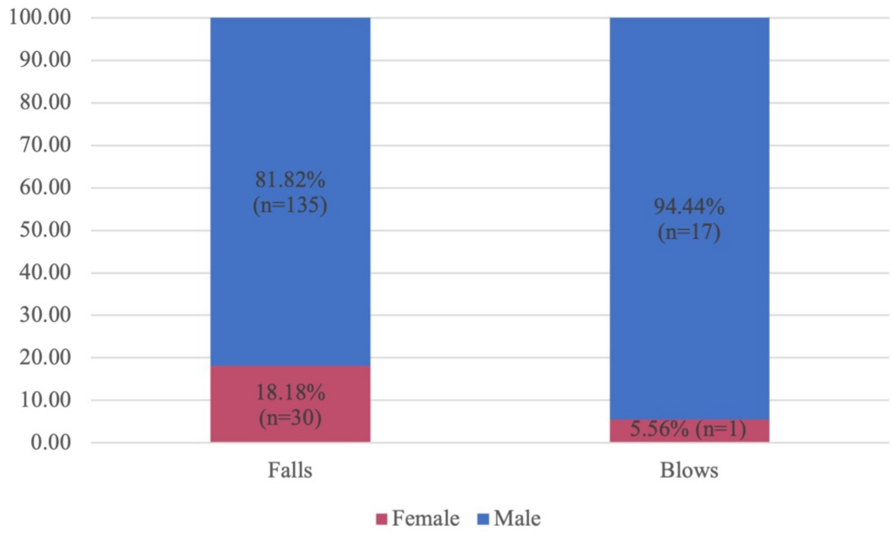

Figure 9: Distribution of the sample from the AP-HM according to the sex

The fall cases are composed of 53 individuals aged 20-29 (82.81%), 49 aged 30-39 (94.23%), and 63 aged 40-49 (94.03%) (Figure 10).

The blow cases are composed of 11 individuals aged 20-29 (17.19%), 3 aged 30-39 (5.77%), and 4 aged 40-49 (5.97%) (Figure 10).

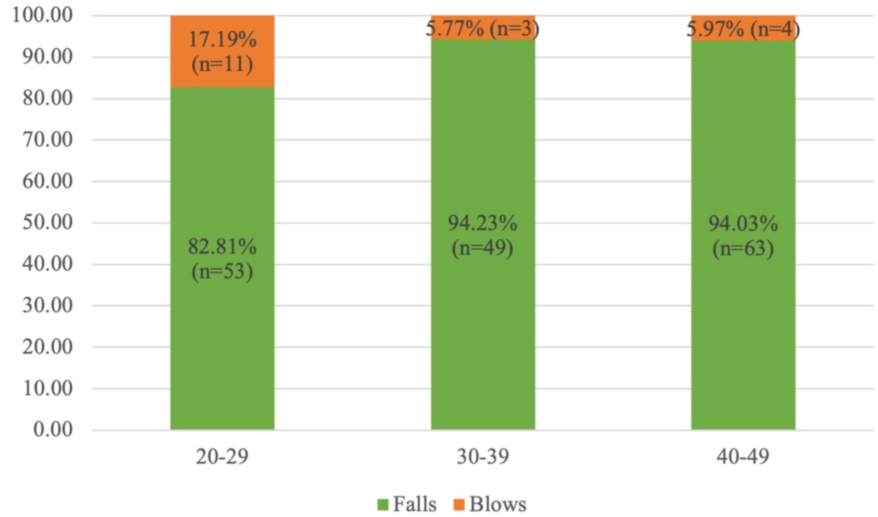

Figure 10: Distribution of the sample from the AP-HM according to the age

1.1.2.2. Coimbra

The sample is composed of 106 individuals of age and sex known. The distribution by age, sex, and etiology, on which the selected skeletal trauma was scored, are presented on the histogram below (Figure 11, Figure 12).

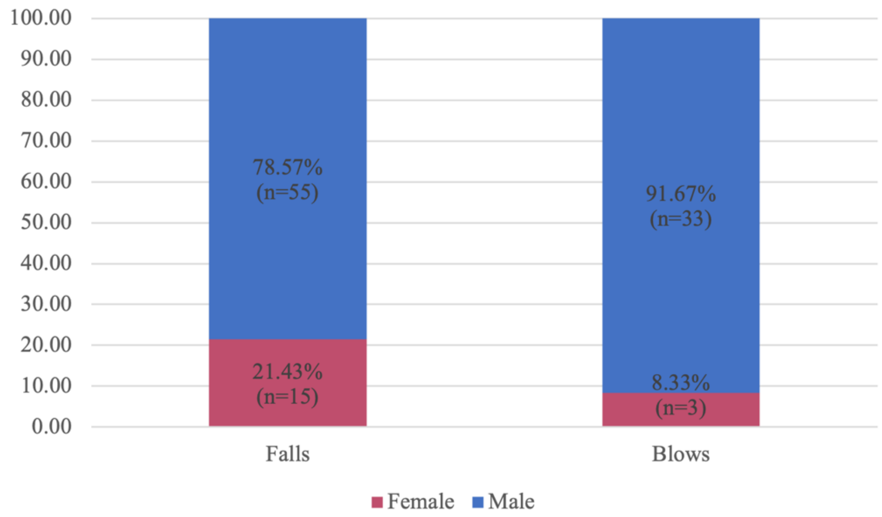

Figure 11: Distribution of the sample from Coimbra according to the sex

The sample from the CHUC consists of 88 men and 18 women aged 20-49; and is more heterogenous concerning the etiology of the last sample (70 falls and 36 blows) (Figure 11).

The fall cases comprise 55 males (78.57%), and 15 females (21.43%).

The blow cases comprise 33 males (91.67%), and 3 females (8.33%).

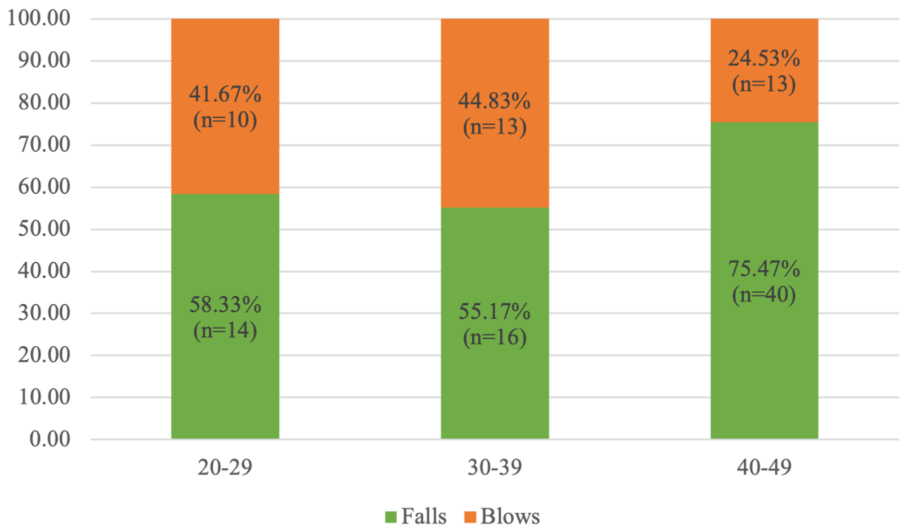

Figure 12: Distribution of the sample from Coimbra according to the age

The fall cases are composed of 14 individuals aged 20-29 (58.33%), 16 aged 30-39 (55.17%), and 40 aged 40-49 (74.47%) (Figure 12).

The blow cases are composed of 10 individuals aged 20-29 (41.67%), 13 aged 30-39 (44.83%), and 13 aged 40-49 (24.53%) (Figure 12).

1.1.2.3. Nancy

The sample is composed of 111 individuals of age and sex known. The distribution by age, sex, and etiology, on which the selected skeletal trauma was scored, are presented on the histogram below (Figure 13, Figure 14).

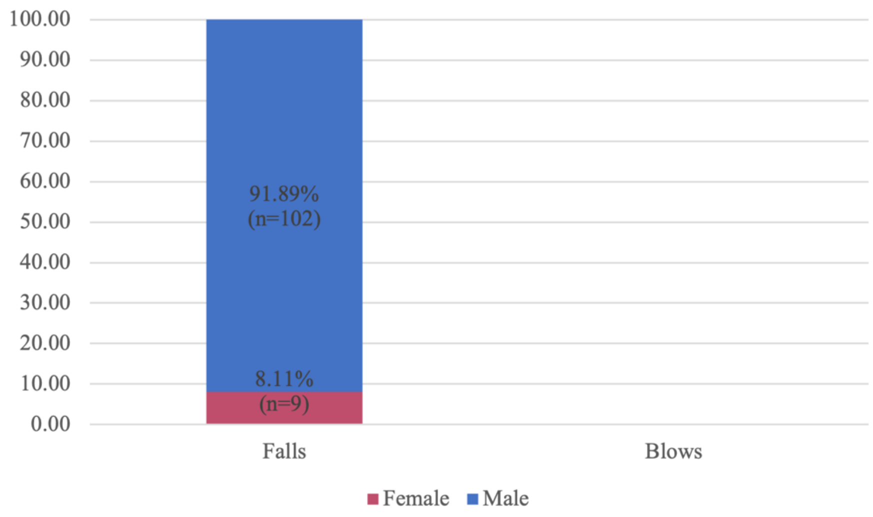

Figure 13: Distribution of the sample from Nancy according to the sex

From the hospital of Nancy, we selected only blow cases. This sample is composed of 102 men and 9 women aged 20-49 (Figure 13).

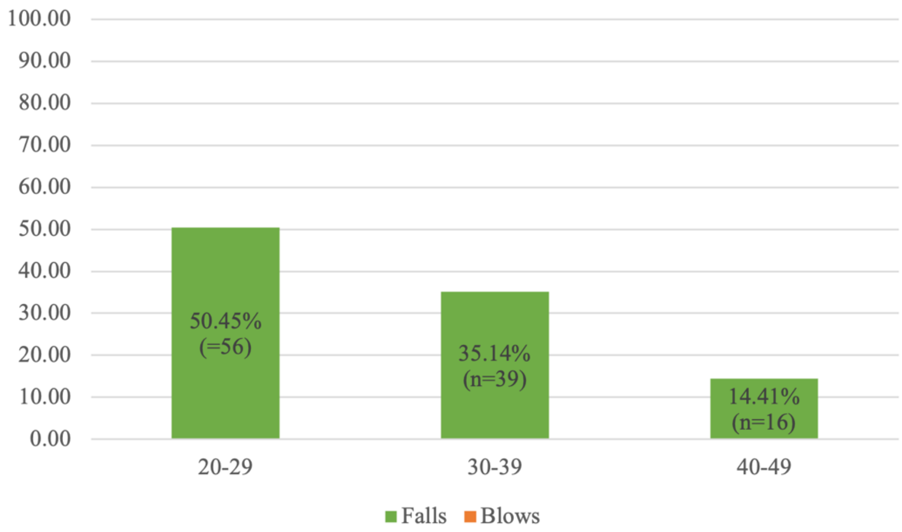

Figure 14: Distribution of the sample from Nancy according to the age

The blow cases are composed of 56 individuals aged 20-29 (50.45%), 39 aged 30-39 (35.14%), and 16 ages 40-49 (14.41%) (Figure 14).

1.2. Forensic cases

1.2.1. The data collection process for method validation

The second stage of the research was to test the method on a forensic sample.

We carried out a retrospective descriptive study from November 2009 to November 2020. All available cases in accordance with our selection criteria have been selected. We included adults aged 20 to 49 who had undergone a forensic autopsy for a trauma clearly identified during the first survey data (fall regardless of the height or blow with or without an object). We had undergone Post-Mortem Computerized Tomography scans (PMCT). A forensic pathologist made the case selection. The scans were from the digital archiving systems of the forensic department of the Assistance Publique-Hôpitaux de Marseille (AP-HM, France). Thus, the analysis of the scans was carried out by an independent anthropologist and blinded to the lesion mode.

The data collected on the autopsy report were made a posteriori and transmitted by the medical examiner.

1.2.2. Selection of fall and blow types of the deceased

The sample comprised 47 anonymized patients. This sample is composed by 34 men and 13 women (Figure 15).

The fall cases comprise 9 males (81.82%), and 2 females (18.18%) (Figure 15).

The blow cases comprise 25 males (69.44%), and 11 females (30.56%) (Figure 15).

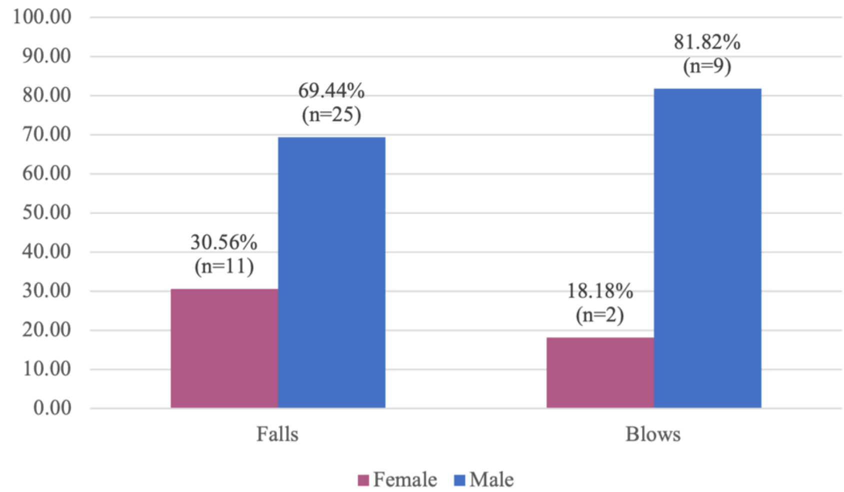

Figure 15: Distribution of the sample of the deceased according to the sex

The fall cases are composed of 16 individuals aged 20-29 (94.12%), 13 aged 30-39 (81.25%), and 7 aged 40-49 (50%) (Figure 16).

The blow cases are composed of 1 individual aged 20-29 (5.88%), 3 aged 30-39 (18.75%), and 7 aged 40-49 (50%) (Figure 16).

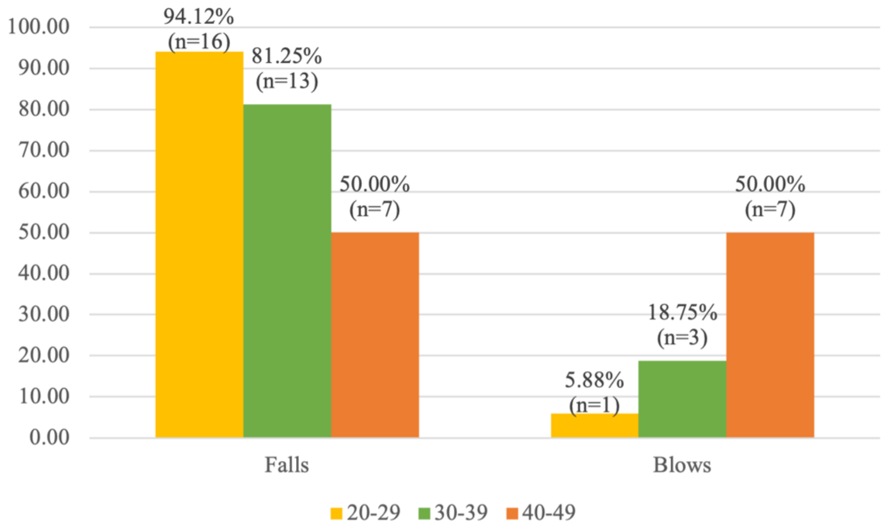

Figure 16: Distribution of the sample of the deceased according to the age

2. Skeletal blunt force trauma protocol

2.1. Fracture classifications

There are many systems of classification of fractures. Still, two are medical systems: the Swiss Arbeitsgemeinshaft für Osteosynthesefragen/Association for the Study of the problems of Internal Fixation (AO/ASIF) for long bones (Müller *et al.*, 1991) and the Orthopaedic Trauma Association (OTA). Nevertheless, for forensic anthropology practice, sometimes it is recommended to use the classification presented by Wedel and Galloway in 2014 (Galloway, 2014a, 2014b; Galloway & Wedel, 2014c, 2014d).

The fracture morphologies registered in this study are presented in Table 15 (Annex III).

2.1.1. OA and OTA classifications

Müller published this classification in 1997 as "the comprehensive classification of fractures of long bones"(Müller *et al.*, 1987). It was used for categorizing long bone fractures. The classification system is based on the localization of fracture (bone and segment), its type (e.g., Simple, wedge, multifragmentary), its geometry (e.g. Transverse, oblique, spiral) and its displacement (e.g. Rotation, angulation).

Since 1990, the classification has been expanded for pelvic, spinal fractures and flat bones.

The Orthopedic Trauma Association (OTA) extended the classification of Müller and published it in 1996 in the Journal of Orthopaedic Trauma (JOT). The compendium was revised in 2007 and 2018 (Marsh *et al.*, 2007; Meinberg *et al.*, 2018).

2.1.1.1. Shoulder Girdle

2.1.1.1.1. Clavicle

To simplify the medical classification, we retained the fractures below (Figure 17):

- Fracture of the lateral extremity
- Fracture of the medial extremity
- Fracture spiral/oblique of the diaphysis
- Fracture transverse of the diaphysis

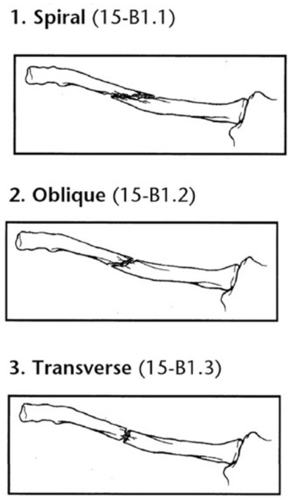

Figure 17: The AO/OTA classification for clavicle fractures (from Marsh et al., 2007, S73)

2.1.1.1.2. Scapula

We used only three groups of the classification (Figure 18):

- Fracture on the body
- Coracoid fracture
- Fracture of the articular surface (anterior rim, posterior rim of inferior rim)

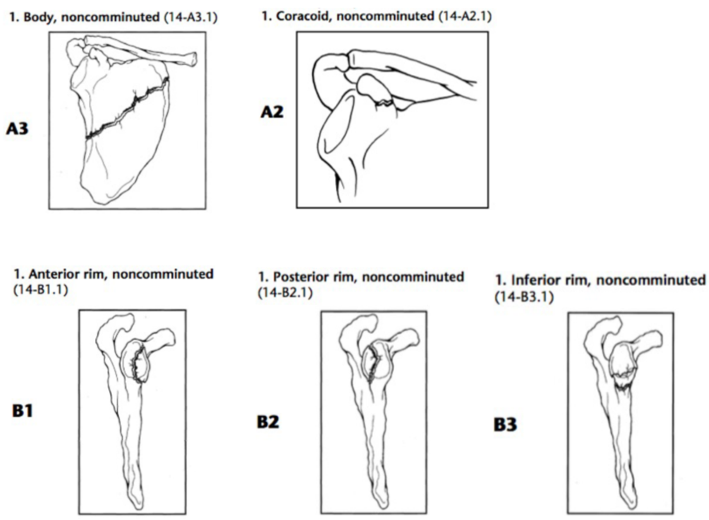

Figure 18: The AO/OTA classification for scapula fractures (from Marsh et al., 2007, S69-70)

2.1.2. Other classifications

The purpose of the AO/OTA classifications is to classify fractures for better patient care; therefore, it is very detailed. They are not recommended for forensic anthropology practice because their intraobserver reliability is poor (Galloway & Wedel, 2014a). Fractures are generally characterized according to their location, completeness of the break, probable point or points of impact, and pattern (Galloway & Wedel, 2014a; Kimmerle & Baraybar, 2008b).

2.1.2.1. Cranial vault and basicranium

The types of fracture presented below apply to the frontal, parietal, occipital, sphenoid, and temporal bones.

The selected fractures were (Figure 19, Figure 20):

- Linear fracture, which is a single fracture that passes through the outer and/or inner table)
- Diastatic fracture, which is a linear fracture involving a suture.
- A depressed fracture is the collapse of the diploe with or without fracture of the outer and/or inner table.

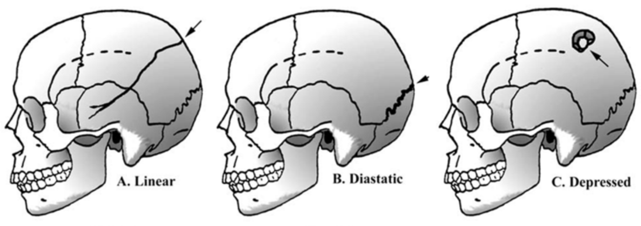

Figure 19: Cranial vault and basicranium fractures (from Galloway, Wedel, 2014c, p. 139)

- A radiating fracture is a crack that extends outward from the point of impact of a fracture.
- A concentric fracture is a fracture in the circumferential around the point of impact

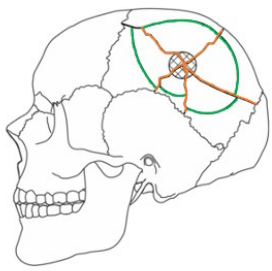

Figure 20: Radiating (orange) and concentric (green) fractures (modified from Christensen et al., 2021, p. 11)

- A comminuted fracture is a fracture composed of more than two fragments. This pattern is the same, whatever the bone involved.
- The pattern mixed fracture did not exist in the literature, it is the combination of two patterns presented below without considering comminuted fracture.

2.1.2.2. Face

2.1.2.2.1. Maxilla

The fractures selected were (Figure 21):

- A fracture le fort I consists of a fracture of the upper palate from the rest of the maxilla, which passes through the maxilla and nasal aperture.
- A fracture le fort II shows fractures of the maxilla, orbits (lower portions), and the upper part of the nasal bones.
- A fracture le fort III is composed of a passing fracture behind the eyes, into the orbits, and through the bridge of the nose.

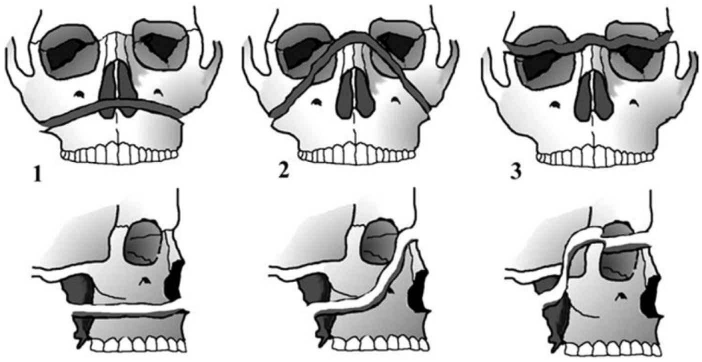

Figure 21: Le Fort fractures of the face (from Galloway, Wedel, 2014c, p. 153)

2.1.2.2.2. Palatine

The classification was divided into:

- Sagittal fracture
- Transverse fracture
- Oblique fracture
- Comminuted fracture
- Mixed fracture combines two patterns presented below without considering comminuted fracture

2.1.2.2.3. Zygomatic Bone

The observed fractures were:

- Isolated fracture of one process
- Tripod fracture (fracture of the three processes)
- Fracture of two processes

- Comminuted fracture
- Mixed fracture combines two patterns presented below without considering comminuted fracture

2.1.2.3. Mandible

The typology depends on the location of the mandibular fracture. Condylar fracture, angle fracture, symphyseal fracture, body fracture, ascending ramus fracture, and coronoid fracture. During the scoring, we observed that some fractures were totally absent, so we decided to group fracture patterns together.

Condylar fracture, angle fracture, ascending ramus, and coronoid fracture became ascending ramus (Figure 22).

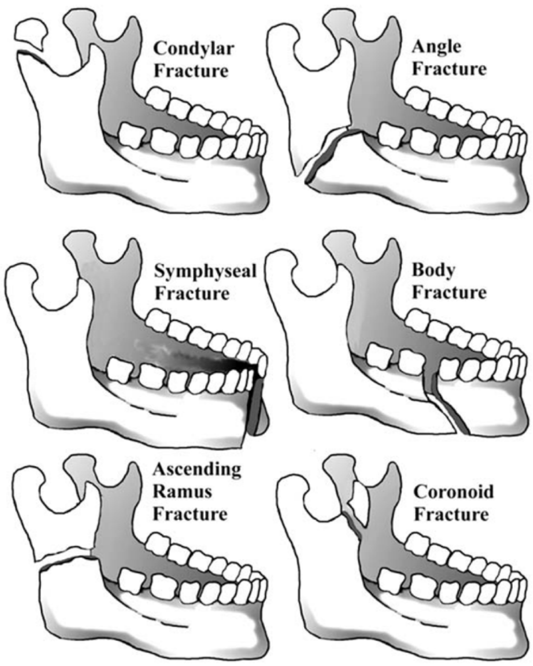

Figure 22: Mandibular fractures (from Galloway, Wedel, 2014c, p. 154)

2.1.2.4. Shoulder Girdle

2.1.2.4.1. Scapula

To complete the selection of fracture on the scapula based on the AO/OTA classification, we gathered two groups (Figure 23):

- Spinal fracture
- Neck fracture (neck fracture lateral to spine, neck fracture through base of spine or transverse neck fracture)

- Comminuted fracture
- Mixed fracture combines two patterns presented below without considering comminuted fracture

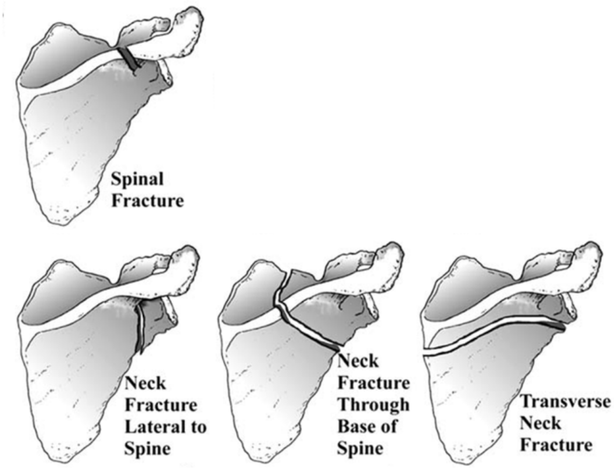

Figure 23: Scapular fracture (from Galloway, 2014a, p. 202)

2.1.2.5. Thoracic Cage

2.1.2.5.1. Ribs

The quotation of ribs fracture was only based on the localization:

- Fracture on the anterior arch
- Fracture on the middle arch
- Fracture on the posterior arch
- Comminuted fracture
- Mixed fracture combines two patterns presented below without considering comminuted fracture

2.1.2.5.2. Manubrium and body of the sternum

We coded the fractures below (Figure 24):

- Transverse fracture
- Longitudinal fracture
- Oblique fracture/backward angulation
- Complete comminuted fracture
- Mixed fracture combines two patterns presented below without considering comminuted fracture
- Partial comminuted fracture

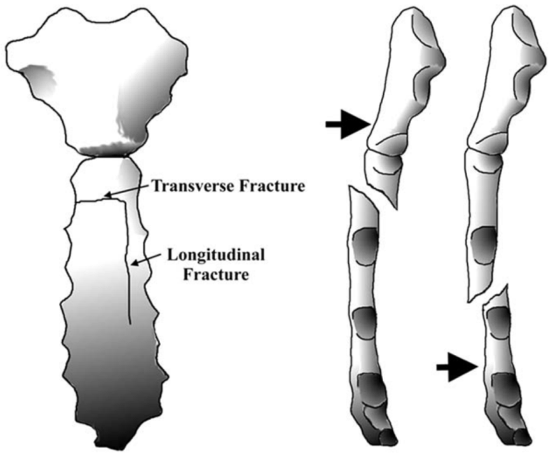

Figure 24: Sternum fractures (from Galloway, Wedel, 2014d, p. 194)

2.1.2.6. Cervical Vertebrae

2.1.2.6.1. Atlas

The fractures selected were (Figure 25):

- Fracture of one arch (anterior or posterior)
- Jefferson fracture (fracture of both arches in two or three part)
- Lateral mass fracture
- Transverse process fracture
- Comminuted fracture
- Mixed fracture combines two patterns presented below without considering comminuted fracture

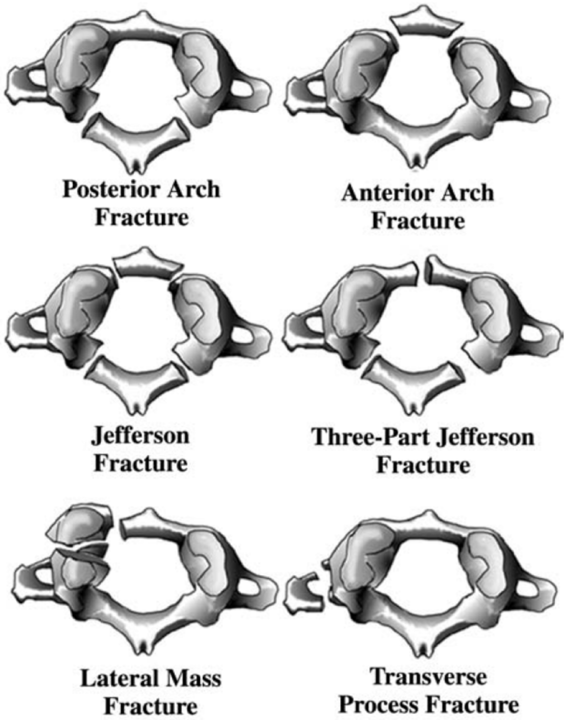

Figure 25: Atlas fractures (from Galloway, Wedel, 2014d, p. 169)

2.1.2.6.2. Axis

The fractures selected were (Figure 26):

- Fracture of the body (teardrop fracture, oblique, horizontal or vertical which can be oriented in the coronal or sagittal plane)
- Transverse process fracture
- Arch fracture (hangman's fracture
- Odontoid fracture or odontoid tip fracture
- Mixed fracture combines two patterns presented below without considering comminuted fracture (i.e. odontoid and body fracture)

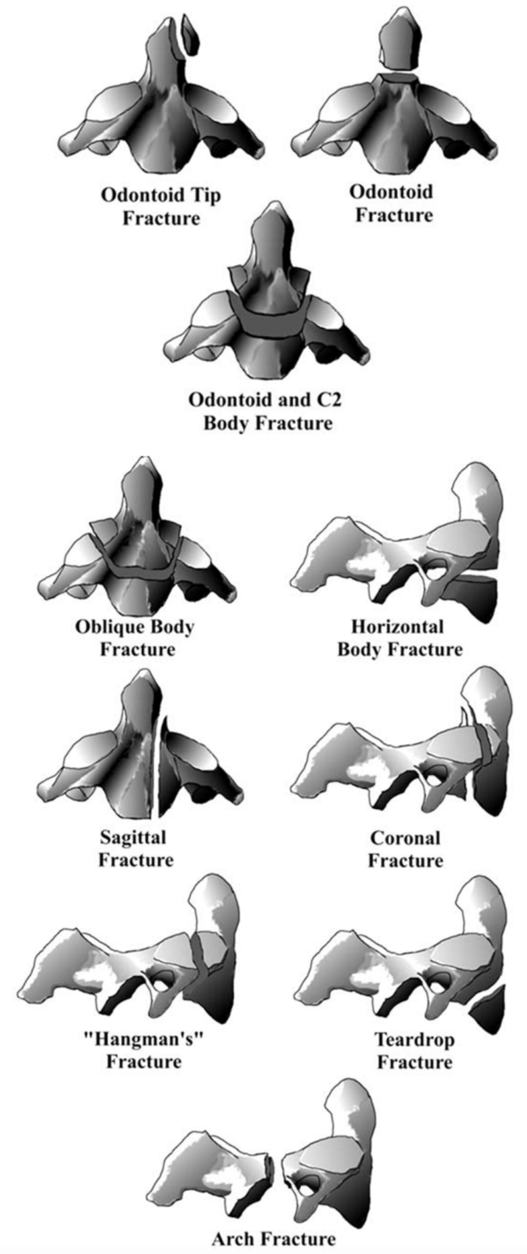

Figure 26: Fractures of the axis (from Galloway, Wedel, 2014d, p. 171 et 173)

2.1.2.6.3. Cervical Vertebrae 3-7

The fractures selected were (Figure 27):

- Fracture of one endplate (superior, inferior or both, i.e., Vertical fracture in sagittal place, tear-drop fracture, pincer fracture, anterior superior margin fracture)
- Compression fracture (superior endplate, inferior endplate or both)
- Spinous process or laminar fracture
- Lateral mass or facet fracture

- Comminuted fracture or burst fracture
- Mixed fracture combines two patterns presented below without considering comminuted fracture

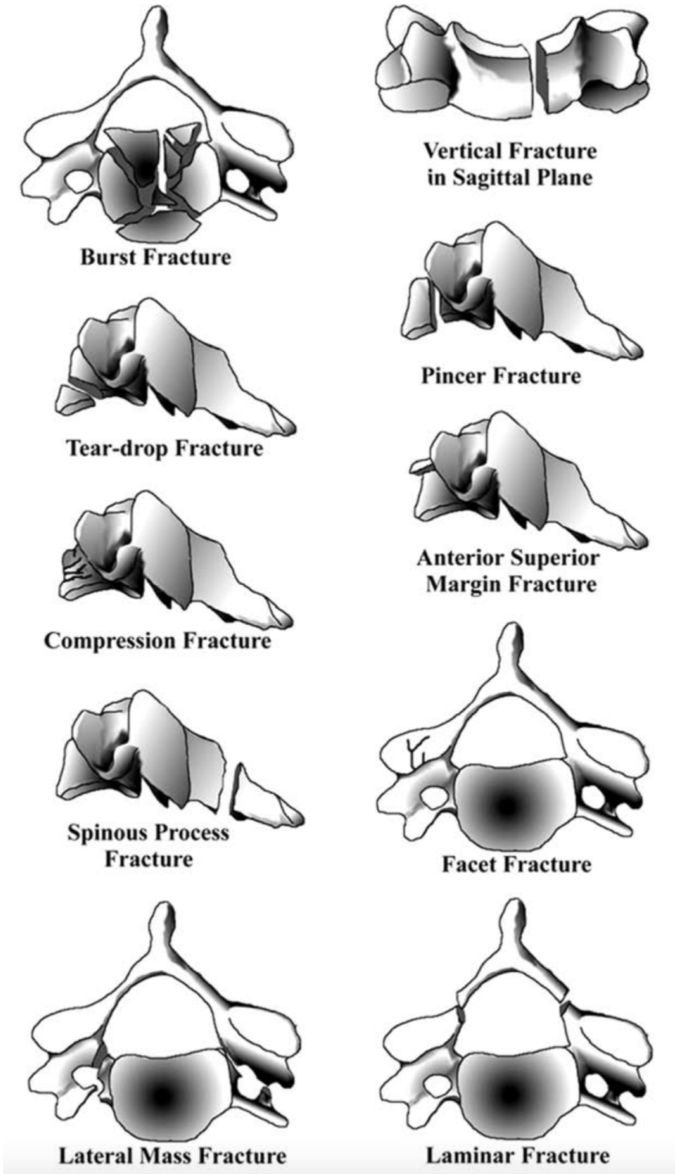

Figure 27: Fractures of the cervical vertebrae 3-7 (from Galloway, Wedel, 2014d, p. 175)

2.1.2.7. Thoracic and Lumbar Vertebrae

The fractures selected were (Figure 28):

- Fracture of one endplate (superior or inferior)
- Compression fracture (superior endplate, inferior endplate or both, anterior cortical fracture, and lateral compression fracture)
- Chance fracture
- Spinous process fracture

- Posterior arch fracture
- Comminuted fracture (fracture of both endplates)
- Mixed fracture combines two patterns presented below without considering comminuted fracture

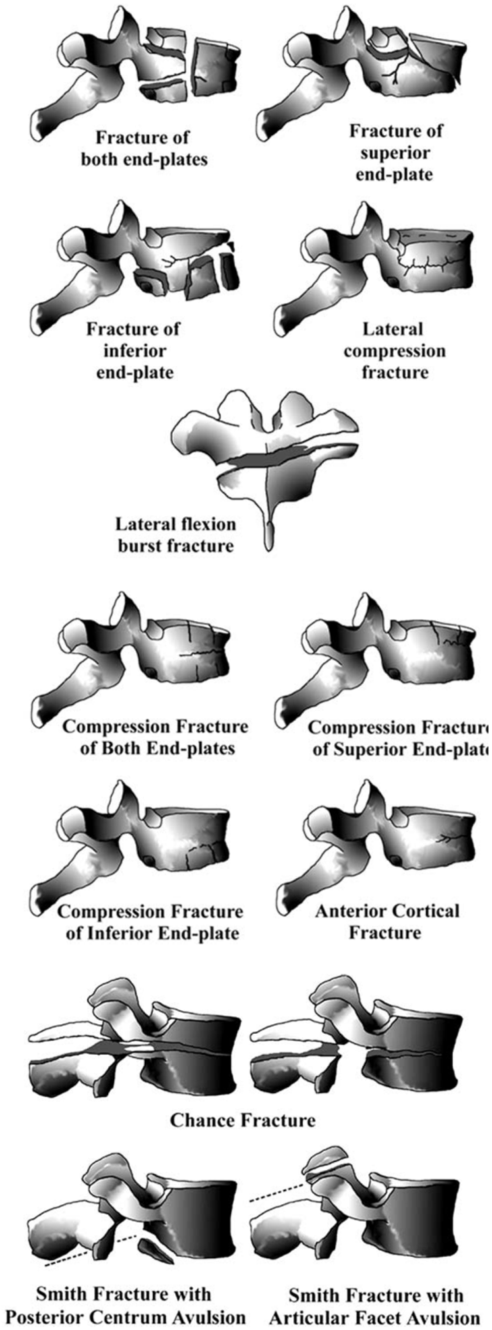

Figure 28: Fracture of thoracic and lumbar vertebrae (from Galloway, Wedel, 2014d, p. 179-182)

2.1.2.8. Pelvic Girdle

2.1.2.8.1. Sacrum

The fractures selected were (Figure 29):

- Transverse fracture
- Lateral mass fracture or vertical fracture
- Juxta-articular or articular fracture
- Cleaving or oblique fracture
- Avulsion fracture
- Comminuted fracture
- Mixed fracture combines two patterns presented below without considering comminuted fracture

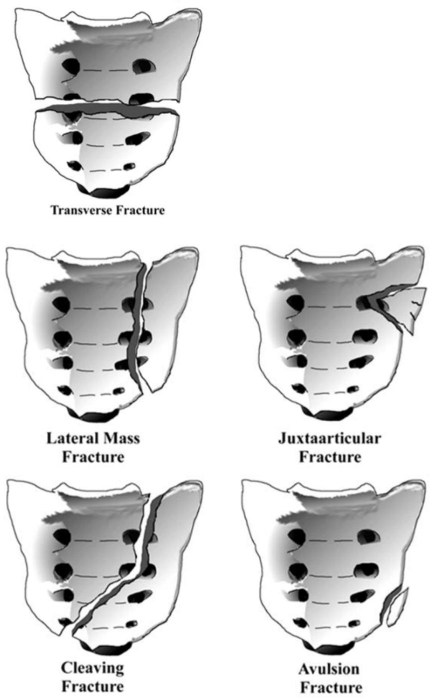

Figure 29: Sacral fractures (from Galloway, Wedel, 2014d, p. 187-188)

2.1.2.8.2. Coxal bone

The fractures selected were (Figure 30):

- Iliac fracture (iliac wing fracture, iliac fracture with sacroiliac joint extension, anterior inferior iliac spine avulsion, and anterior superior iliac spine avulsion)
- Sacroiliac fracture
- Acetabular fracture
- Fracture of the pubis (pubic rami fractures, and pubic symphysis separation)
- Fracture of the ischium (ischial fracture, and ischial tuberosity avulsion)
- Comminuted fracture

- Mixed fracture combines two patterns presented below without considering comminuted fracture

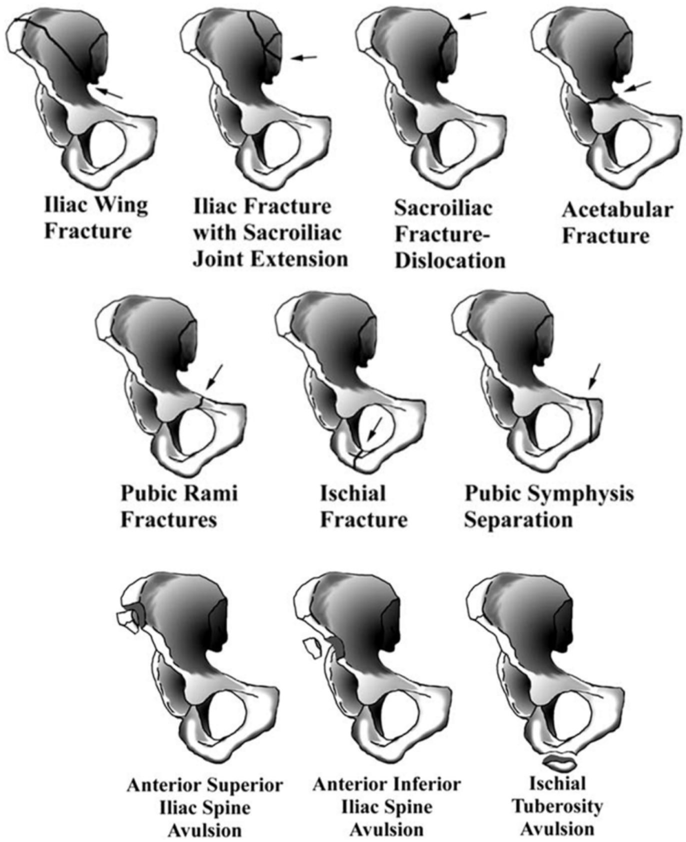

Figure 30: Fractures of the coxal bone (from Galloway, 2014b, p. 247 et 257)

2.1.2.8.3. Acetabulum

The fractures selected were (Figure 31):

- Fracture of the posterior wall or column
- Fracture of the anterior wall or column
- Transverse fracture
- T-shaped fracture, anterior and posterior hemitransverse, and bicolumn
- Mixed fracture combines two patterns presented below without considering comminuted fracture (i. e. Posterior wall and transverse)
- Comminuted fracture (i.e. Posterior wall and column)

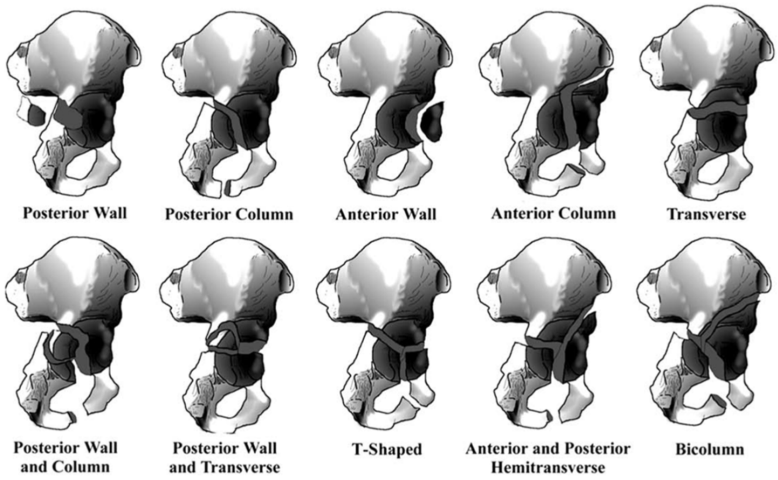

Figure 31: Fractures of the acetabulum (from Galloway, 2014b, p. 256)

2.1.2.9. Femur

2.1.2.9.1. Femur head neck

The fractures selected were (Figure 33):

- Inferior head fracture
- Superior head fracture
- Adduction
- Abduction
- Basicervical fracture
- Comminuted fracture
- Mixed fracture combines two patterns presented below without considering comminuted fracture (i. e. Posterior wall and transverse)

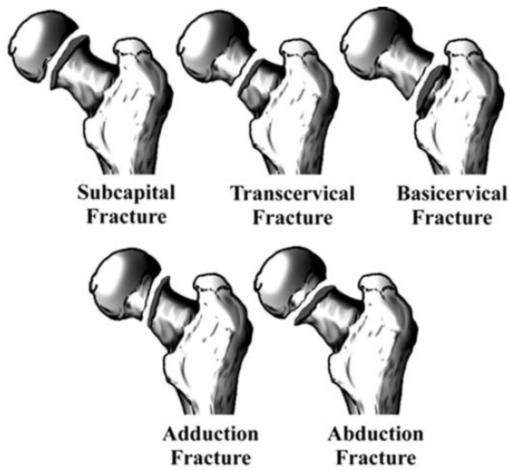

Figure 32: Fractures of the femur head neck (from Galloway, 2014b, p. 260)

2.1.2.9.2. Femur Trochanter

The fractures selected were (Figure 33):

- Two-part intertrochanteric fracture
- Intertrochanteric fracture with the detachment of lesser trochanter or of the trochanter
- Two-part subtrochanteric fractures
- Fracture of the great trochanter
- Comminuted fracture (i.e. Fracture with reverse obliquity, all the three-part fractures, four-part and five-part fractures)
- Mixed fracture combines two patterns presented below without considering comminuted fracture (i. e. Posterior wall and transverse)

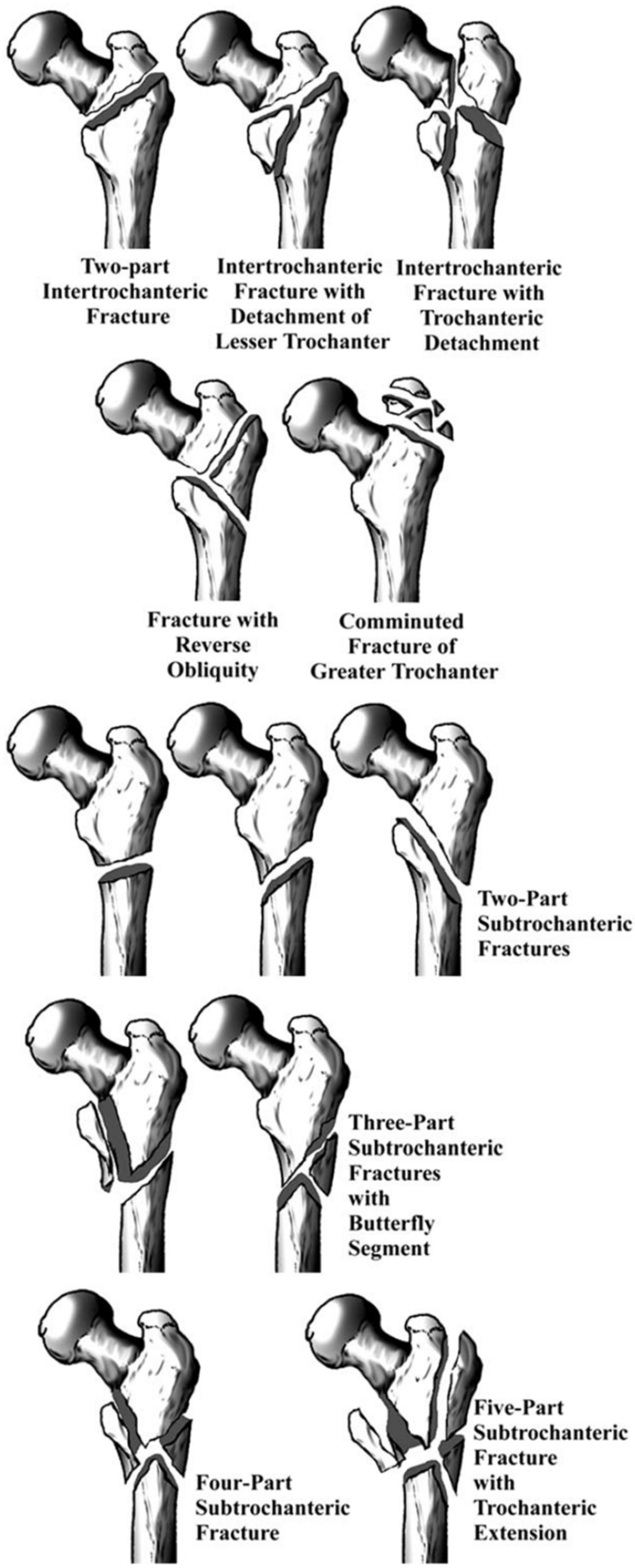

Figure 33: Fractures of the femur (from Galloway, 2014b, p. 262 et 265)

2.1.2.10. Other fractures

For the other fractures, the quotation was made by localization and according to the absence and the presence of a fracture. For more details, please refer to the Table 15 (Annex III).

2.2. Limitations

Special attention must be paid to discrete traits (i.e. spina bifida, os odontoideum, defective fusion of the vertebral arches) (Ankith *et al.*, 2019; Verna, 2014) (Figure 34).

Figure 34: Spina bifida occulta of the atlas (Verna, 2014, p. 75)

Some of these may appear to be fractures, and the volume rendering (VR) can help with scoring (Figure 35).

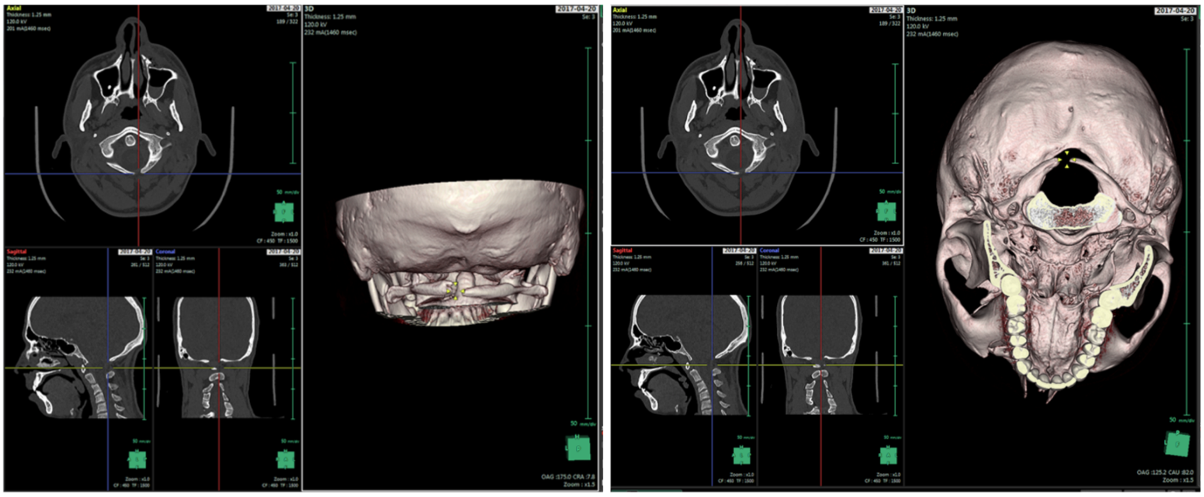

Figure 35: Example of a spina bifida occulta of the atlas identified in this study in multiplanar reconstructions (MPR) and volume rendering (VR)

2.3. Obtaining data: Computed Tomography parameters

The data obtained are anonymized. Only the sex, age, and etiology of the trauma (height of fall, the object used on blow) of the individual are reported.

2.3.1. Living cases

2.3.1.1. Marseille

The study sample is composed of images from individuals scanned over a period of December 2008 to December 2016. These images are retrieved from the PACS (Picture Archiving and Communication System) of the Marseille Public Hospital (AP-HM). In DICOM (Digital Imaging and Communication in Medicine) Format. The scan slices are obtained from a "64-Row Multidetector CT" (Somatom 64, Siemens, Erlangen, Germany). The scanner parameters are 120 Kv, 50-150mas and a slice thickness of 0.6 mm.

One type of medical indications for scanning were selected: polytraumatic. The scanners in case of polytrauma allow an area from the first cervical to the upper part of the femur.

2.3.1.2. Coimbra

We used the digital archive of CHUC's (Coimbra University Hospital Centre) Radiology Department, to choose examinations of CT scans performed over a period of June 2011 to April 2019. These examinations were acquired with a "16-Row Multidetector CT" (Somaton Emotion, Siemens, Erlangen, Germany). The scanner parameters are 123 Kv, 220mas and a slice thickness of 1.25 mm.

2.3.1.3. Nancy

The study sample is composed of images from individuals scanned over a period of December 2008 to May 2019. These images are retrieved from the PACS (Picture Archiving and Communication System) of the Nancy Hospital (CHRU) In DICOM (Digital Imaging and Communication in Medicine) format. The scan slices are obtained from a "16-Row Multidetector CT" (Sensation 16, Siemens, Erlangen, Germany). The scanner parameters are 120 Kv, 80-150mas and a slice thickness of 0.5 Or 1.25 mm (depending on the type of examination).

Four types of medical indications for scanning were selected: fracture of the skull and of the face, fracture of the neck, fracture of rib(s), sternum and thoracic spine, and fracture of the lumbar spine and pelvis.

2.3.2. Forensic cases

We carried out a retrospective descriptive study from November 2009 to November 2020, all available cases following our selection criteria have been selected. PMCT records were extracted from the forensic report and the digital archiving systems of the Forensic Department

of The Assistance Publique-Hôpitaux de Marseille (AP-HM, France). The CT devices used were a Siemens Somatom Definition (Siemens Healthineers Headquarters: Erlangen, Germany) and a General Electrics Optima CT 660 (GE Healthcare Headquarters: Chicago, IL, USA). Whenever possible, the body was in a supine position, arms resting along the body. Two acquisitions were made with 1mm sections: cervicocranial and from the cervical region to the feet. However, sometimes, we may only have one acquisition.
We collected the following data on the autopsy reports: gender and age (later referred as 'baseline'), and whether the death was due to falls or blows.

2.4. Recording Skeletal Trauma using Computed Tomography

Scoring of selected fractures is done in three ways:
- According to the law of all or nothing, that is, according to its absence (0) or presence (1)
- According to the morphology of fracture
-According to the minimum number of fractures: absence (0), simple fracture (1) and multiple fracture (2)

2.4.1. Living cases

2.4.1.1. Marseille

We observed the individual in DICOM slices with advantage 4D ® software in the sagittal, coronal, and axial planes (Figure 134). With a bone reconstruction, the “volume rendering” function allows visualization of the individual skeleton in 3 dimensions. These two functions are used to view and rate selected morphologies of fracture.

2.4.1.2. Coimbra

We observed the individual in DICOM slices with Osirix ® software in the sagittal, coronal, and axial planes (Figure 134). With a bone reconstruction, the “volume rendering” function allows visualization of the individual skeleton in 3 dimensions. These two functions are used to view and rate selected morphologies of fracture.

2.4.1.3. Nancy

We observed the individual in DICOM slices with Synapse Mobility ® software in the sagittal, coronal, and axial planes (Figure 134). With a bone reconstruction, the "volume rendering" function allows visualization of the individual skeleton in 3 dimensions. These two functions are used to view and rate selected morphologies of fracture.

2.4.2. Forensic cases

We observed the individual in DICOM slices with Osirix ® software in the sagittal, coronal, and axial planes (Figure 134). With a bone reconstruction, the "volume rendering" function allows visualization of the individual skeleton in 3 dimensions. These two functions are used to view and rate selected morphologies of fracture.

2.5. Statistical Analysis

Statistical analyses were performed using R software® version 4.1.3 (R foundation for statistical computing, Vienna, Austria).

Fisher's exact tests were used to identify the association between two qualitative variables, especially the association between the presence/absence of fracture and the sex or age group.

The Mean Measure of Divergence (MMD) was used to calculate distances between the two etiologies (the mean-variance) from the presence/absence of fracture recorded in binary scoring (Corruccini, 1974; Sjøvold, 1973, 1977). MMD values of more than twice their corresponding standard deviation are considered statistically significant, allowing us to consider that compared samples diverge. We used {AnthropMMD} R package.

The Mann-Whitney U Test was used to compare the mean number of fractures of the two etiologies for each anatomical region.

The decision tree was used to predict the etiology of trauma based on the number of fractures in the different anatomical regions recorded in three stages (absence/presence of one fracture/presence of two fractures and more). We used {rpart} R package.

Inter and intra-observer variations were evaluated using Cohen's kappa coefficient with {KappaGUI} R package.

Using the available etiology, the random forest was used to predict the circumstances of observed fractures, that is, a blow or a fall. This approach is adapted to classification problems that include qualitative and quantitative variables. The dataset was randomly partitioned in 300 patients for the training set to create a methodology, and 100 patients for the testing set, the latter being never "seen" by the model while training, to assess the effectiveness of this method in predicting the etiology of fractures in new patients. We used the following packages: *randomForest* to model and predict using random forests, *pROC* to calculate ROC curves, *tidyverse* for general data manipulation, programming, and data visualization.

Chapter 4. Results and Discussion

1. Distinction between blows and falls by localization and the number of fractures

The obtained data was used on the published original paper:

Mélanie Henriques, Bérengère Saliba-Serre, Laurent Martrille, Alain Blum, Kathia Chaumoître, Paulo Donato, Nuno Campos, Eugénia Cunha, Pascal Adalian. **Discrimination between falls and blows from the localization and the number of fractures on computed tomography scans of the skull and the trunk**. Forensic Sciences Research, Volume 8, Issue 1, March 2023, Pages 30–40. https://doi.org/10.1093/fsr/owad006

1.1. Introduction

One of the key roles of the forensic anthropologist, in collaboration with the pathologist, is to provide analysis and interpretation of skeletal trauma. They can afford an expert opinion on the death circumstances by inferring the mechanism of trauma from the skeletal fractures (Kranioti, 2015; Passalacqua & Fenton, 2012).

Blunt force trauma (BFT) can be caused by a blunt object or a surface, as in transportation fatalities, falls, or interpersonal violence (Ambade & Godbole, 2006; Sterzik *et al.*, 2016; Wedel & Galloway, 2014). The highly variable nature of this type of trauma makes it complicated and difficult to interpret, on the basis of the skeletal characteristics only.

Moreover, BFT is one of the most common injuries encountered by the forensic expert (Kranioti, 2015). Therefore, the expert has to try to determine if the injury is induced by blows or related to a fall (Kranioti, 2015; Kremer & Sauvageau, 2009). To achieve this, the Hat Brim Line rule (HBL) has often been used (Ehrlich & Maxeiner, 2002; Guyomarc'h *et al.*, 2010; Kremer & Sauvageau, 2009; Maxeiner & Ehrlich, 2000). Nevertheless, this distinction remains a challenge, mainly because of a lack of objectivity and standardized methods.

This study aims to investigate whether circumstances of traumatic events have an influence on the fractures they create and on their distribution on the skeleton (skull and trunk).

If so, the second objective will be to check whether we can propose a method helping to define the etiology of observed fractures.

1.2. Material and methods

1.2.1. Study sample

A retrospective review of post-traumatic living individuals who were CT-scanned between 2008 and 2019 identified 400 cases of falls and blows, with at least one fracture. CT-scans of these polytraumatized individuals were performed at the Assistance Publique-Hôpitaux de Marseille (AP-HM, France), the Centro Hospitalar e Universitário de Coimbra (CHUC, Portugal) and the Centre Hospitalier Regional et Universitaire de Nancy (CHRU, France). These scans were anonymized and collected from the PACS (Picture Archiving and Communication System). The clinical management of the patients rarely required a full-body scan. According to medical indications of CT scans, the skeleton had to be considered in two parts: on the one hand, the cranium and the mandible; and, on the other hand, from the first cervical to the pelvis, without the appendicular skeleton (i.e. the spine, the thorax, the shoulder and pelvic girdles and the upper end of the femur).

The scanner slices were 0.6 mm and 1.25 mm thick according to the acquisition protocol. We selected adults aged between 20 and 49 years old, in order to have a certain homogeneity in the physicochemical properties of the bone.

Medical information for each of these cases was reviewed, as well as case details relevant to the circumstances causing the BFT. Since this is a retrospective study, based on clinical management of a patient, not all information about the circumstances of fractures is systematically indicated. So, we have no data on the number of perpetrators or blows in blow injuries. Furthermore, whenever possible, the characteristics of the individuals were recorded. Details included the following data:

Circumstances of blunt force trauma:

- Date of the traumatic event
- Type of blunt force trauma (falls or blows)
- Date of CT scan
- Height of the fall (when the medical report gives this information)
- Blunt force object used (when the medical report gives this information)

Characteristics of the individuals:

- Age
- Sex

Following the standards of the National Consultative Ethics Committee for health and life sciences (CCNE), National Council of Ethics for the Life Sciences (CNECV), and the Helsinki

Declaration of 1975 concerning the privacy and confidentiality of personal data, all personal patient information was anonymized. Only age, sex, and date of examination were known for each subject.

1.2.2. Variables

We selected 14 anatomical regions: basicranium, cranial vault, face, mandible, clavicle, scapula, sternum, ribs, cervical vertebrae, thoracic vertebrae, lumbar vertebrae, sacrum, coxal bone and femur. Fractures on the basicranium comprise those of the cribriform plate of the ethmoid bone, the orbital plate of the frontal bone, the temporal bone, the sphenoid, and the occipital bone (Cooper & Golfinos, 2000). Given the definition of Golfinos and Cooper (Cooper & Golfinos, 2000) and for the purposes of descriptive statistics, we only considered as vault elements : the frontal and parietal bones. The face is composed of the maxilla, the palatine, the vomer, the lacrimal bones, the nasal bones, the zygomatic and the ethmoid bones without the cribiform plate. We grouped together cervical vertebrae and hyoid bone (Cooper & Golfinos, 2000; Rowbotham *et al.*, 2018c).

Skeletal trauma was described for each individual as follows: the skeletal element, anatomical location of the injury (to investigate the distribution of the fractures on the body).

To record the presence of fractures in each anatomical region, we used a binary scoring (0 absence/1 presence); however, to take into account the number of fractures, we used a 3 staged score: 0 absence of fractures, 1 single fracture, 2 two fractures or more.

Each individual was reviewed in the three anatomical planes (axial, coronal, and sagittal) using the window viewing presets for bone and adjusted manually on AW Workstation (AW server 2.0, GE HealthCare, Milwaukee, US) and Horos (version 3.3.5®, © 2021 Horos Project). Three-dimensional volume renderings were also used to identify the fractures.

1.2.3. Statistical analyses

Fisher's exact tests were used to identify the association between two qualitative variables and specially the correlation between the fracture and the sex or the age group. Then, we used the Mean Measure of Divergence (MMD), which is the most common procedure for calculating distances (the mean variance) from a set of non-metric traits recorded in binary scoring (Corruccini, 1974; Sjøvold, 1973, 1977). MMD values of more than twice their corresponding standard deviation are considered statistically significant and allowed us to consider that compared samples diverge.

To compare the mean numbers of fractures of the two etiologies for each anatomical region, the Mann-Whitney U Test was used.

Using the number of fractures on the different anatomical regions recorded in three different stages (absence/presence of one fracture/presence of two fractures and more), a decision tree was built to predict the etiology of these fractures (falls/blows).

All statistical analyses were performed using the R Software® version 3.3.2 (R Foundation for Statistical Computing, Vienna, Austria). For all statistical tests, the significant level used was 0.05. We used {AnthropMMD} R package to calculate the distance between the 2 etiologies regarding the presence of fractures in 14 different anatomical regions. {rpart} R package was used to build the decision tree.

To assess the repeatability, we randomly selected 30 individuals of the sample. The presence and number of fractures were observed twice in fourteen anatomical regions by the same observer, trained on Horos version 3.3.5®. Inter and intra-observer errors were evaluated using Cohen's kappa coefficient with {KappaGUI} R package.

1.3. Results

1.3.1. Inter- and intra-observer errors

The inter- and intra-observer errors were evaluated using Cohen's Kappa (Table 1) (Cohen, 1968; Cohen, 1960). A table taken from Landis And Koch (Landis & Koch, 1977) was used for agreeing to evaluation (Table 2) .

Table 1: Inter- and intra-observer errors of the assessment of the presence and the number of fractures on fourteen anatomical regions using Cohen's Kappa ("-":the kappa was not provided because the calculation made no sense)

Anatomical Region	Absence/Presence		Absence/Simple/Multiple	
	Inter-observer	Intra-observer	Inter-observer	Intra-observer
Basicranium	0.71	1	0.72	1
Cranial Vault	0.84	1	0.84	1
Face	0.9	0.9	0.91	0.82
Mandible	0.87	1	0.75	1
Clavicle	1	0.65	1	0.65
Scapula	0.84	1	0.84	1
Sternum	-	-	-	-
Ribs	0.72	1	0.68	0.93
Cervical V.	1	1	1	1
Thoracic V.	0.76	0.84	0.77	0.68
Lumbar V.	0.92	1	0.92	0.93
Sacrum	1	1	0.86	1

Coxal	1	0.87	1	0.87
Femur	1	1	1	1

Table 2: Agreement by Landis, Koch (1977)

Kappa (k)	Strengh of agreement
<0	Poor
0.00 - 0.20	Sight
0.21 - 0.40	Fair
0.41 - 0.60	Moderate
0.61 - 0.80	Substantial
0.81 - 1.00	Perfect

The results show a perfect and substantial agreement for all variables. The lowest value of Cohen's kappa for the presence/absence of the fracture is 0.65 and for the scoring in three stages 0.65.

1.3.2. Characteristics of the sample

Our sample includes 235 falls and 165 blows from three hospitals, CT-scanned from January 2008 to August 2019. We observed 190 males and 45 females in fall cases, and 152 males and 13 females in blow cases. The sample distribution by sex for each aetiology is shown in Figure 36 and by age groups in Figure 37.

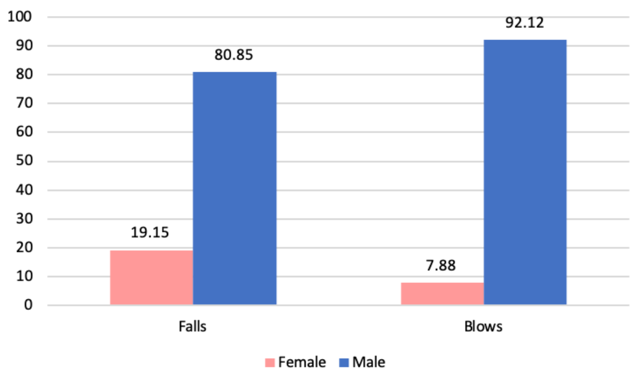

Figure 36: Distribution of the sample by sex for each etiology

We observe 80.85% of males involved in falls and 19.15% of females (Figure 36). In blow cases, 92.12% are males and 7.88% are females (Figure 36). Fisher's exact test shows that the proportion of males significantly differs between the two etiologies (*p*=0.001).

The distribution of age groups in falls is documented below in Figure 37 and supplementary table 1. Adults aged 40-49 years involved in falls are more frequent (43.83%) than the two other age groups (27.66 % for individuals between 30 and 39 years; 28.51% for the group 20-29 years).

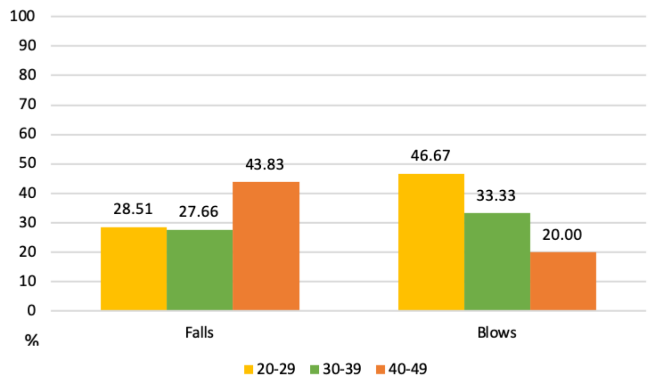

Figure 37: Distribution of the sample by age for each etiology

Among the blow cases, almost the half (46.67%) was 20-29 years old (Figure 37). We recorded 33.33% of individuals aged 30-39 years and 20% aged 40-49 years (Figure 37).
Fisher's exact test shows a significant difference in the distribution of the individuals by age group between the two etiologies (*p*<0.001).

1.3.3. Skeletal fractures: circumstances, incidence, topography

An examination of the distribution and frequency of skeletal fractures showed that almost all skeletal elements were susceptible to fracture in both etiologies (Table *3*, Table *4*, Figure 38).

Table 3: Anatomical Regions (AR) fractured by etiology.

	1 AR fractured		More than 1 AR fractured	
	n	%	n	%
Falls (N=235)	82	34.89	153	65.11
Blows (N=165)	111	67.27	54	32.73

Among the 235 falls, 34.89% (*n*=82) of cases exhibited trauma to a single region and 65.11% (*n*=153) of cases exhibited polytrauma. Among the 165 blows, 67.27% (*n*=111) of cases exhibited trauma to a single region and 32.73% (*n*=54) of cases exhibited polytrauma (Table *3*).

Table 4: Presence of fractures by anatomical region, in both etiologies (p value associated with the Fisher's exact test; in bold: significant values)

	Falls (N=235)		Blows (N=165)		*p value*
	n	%	n	%	
Basicranium	63	26.81	36	21.82	0.290
Cranial Vault	47	20.00	16	9.70	**0.005**
Face	79	33.62	106	64.24	**<0.001**
Mandible	14	5.96	64	38.79	**<0.001**
Clavicle	9	3.83	0	0.00	**0.012**
Scapula	27	11.49	1	0.61	**<0.001**
Sternum	15	6.38	0	0.00	**<0.001**
Ribs	63	26.81	5	3.03	**<0.001**
Cervical V.	14	5.96	0	0.00	**<0.001**
Thoracic V.	47	20.00	3	1.82	**<0.001**
Lumbar V.	82	34.89	8	4.85	**<0.001**
Sacrum	49	20.85	0	0.00	**<0.001**
Coxal	54	22.98	2	1.21	**<0.001**
Femur	20	8.51	0	0.00	**<0.001**

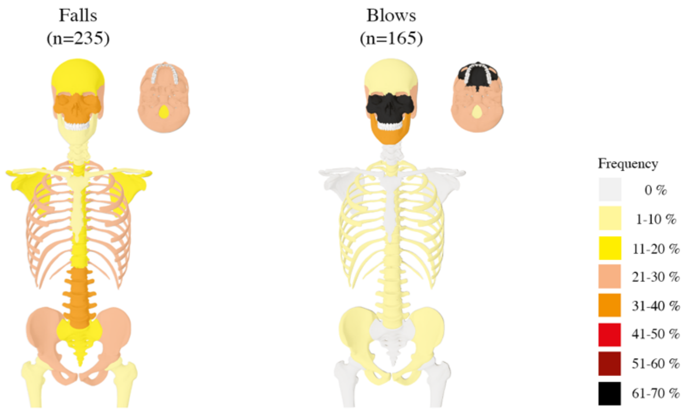

Figure 38: The frequency and distribution of fractures as related to the etiology

We observed that fractures occurred more frequently on the cranial vault, the basicranium, the clavicle, the scapula, the sternum, the ribs, the cervical vertebrae, the thoracic vertebrae, the lumbar vertebrae, the sacrum, the coxal bone and the femur in falls, while fractures of the face (64.24%, *n*=106) and of the mandible (38.79%, *n*=64) occurred more often in blows (Table *4*, Figure 38).

Fractures of the face, the thoracic and lumbar vertebrae, the sacrum, and the coxal bone were significantly associated with sex. Fractures on the mandible, the ribs, and lumbar vertebrae were significantly associated with age (Table 5).

Table 5: Presence of fractures by anatomical region, by sex and age (p value associated with the Fisher's exact test; in bold: significant values)

	Sex		*p*	Age			*p*
	Female (n=58)	Male (n=342)		20-29 (n=144)	30-39 (n=120)	40-49 (n=136)	
Basicranium	22.41	25.15	0.743	28.47	23.33	22.06	0.440
Cranial Vault	15.52	15.79	1.000	19.44	15.00	12.50	0.279
Face	32.76	48.54	**0.032**	47.92	47.50	43.38	0.711
Mandible	12.07	20.76	0.152	27.08	21.67	9.56	**<0.001**
Clavicle	1.72	2.34	1.000	2.08	1.67	2.94	0.839
Scapula	5.17	7.31	0.782	4.17	6.67	10.29	0.135
Sternum	5.17	3.51	0.465	3.47	1.67	5.88	0.223
Ribs	18.97	16.67	0.705	9.03	18.33	24.26	**0.002**
Cervical V.	5.17	3.22	0.438	2.78	4.17	3.68	0.840
Thoracic V.	25.86	10.23	**0.002**	10.42	12.50	14.71	0.548
Lumbar V.	36.21	20.18	**0.010**	15.97	21.67	30.15	**0.018**
Sacrum	22.41	10.53	**0.016**	10.42	12.50	13.97	0.670
Coxal	24.14	12.28	**0.023**	10.42	20.00	12.50	0.075
Femur	8.62	4.39	0.188	4.86	5.83	4.41	0.882

The MMD was calculated from the presence/absence of fractures in the fourteen anatomical regions. The MMD value (0.341) is greater than twice the standard deviation (0.004), indicating a significant difference between falls and blows.

1.3.4. Number of skeletal fractures

Concerning the minimum number of fractures in the fourteen anatomical skeletal regions, we worked in two steps. First, we compared the mean number of fractures occurring in falls and blows (Table *6*). The results show a significant difference between falls and blows based on the number of fractures, on all anatomical regions except the basicranium. Fractures are more numerous in falls than in blows except for the basicranium.

Table 6: Comparison of the minimum number of fractures by anatomical region according to the cause of the trauma (in bold: significant values; -: no fracture was observed so the comparison was not possible)

	FALLS		BLOWS		*p-value*
	[min;max]	mean (s.d.)	[min;max]	mean (s.d.)	Mann-Whitney U test
Basicranium	[0;7]	0.762 (1.629)	[0;8]	0.467 (1.182)	0.295
Cranial Vault	[0;4]	0.366 (0.833)	[0;4]	0.212 (0.651)	**0.023**
Face	[0;8]	0.813 (1.614)	[0;6]	1.370 (1.639)	**<0.001**
Mandible	[0;2]	0.111 (0.439)	[0;2]	0.558 (0.768)	**<0.001**
Clavicle	[0;2]	0.060 (0.315)	-	-	-
Scapula	[0;2]	0.174 (0.514)	[0;1]	0.006 (0.078)	**<0.001**
Sternum	[0;2]	0.077 (0.311)	-	-	-
Ribs	[0;21]	1.362 (2.98)	[0;13]	0.230 (1.455)	**<0.001**
Cervical V.	[0;11]	0.157 (0.880)	-	-	-
Thoracic V.	[0;13]	0.545 (1.511)	[0;2]	0.030 (0.232)	**<0.001**
Lumbar V.	[0;12]	1.132 (2.007)	[0;7]	0.127 (0.709)	**<0.001**
Sacrum	[0;4]	0.391 (0.847)	-	-	-
Coxal	[0;2]	0.409 (0.776)	[0;2]	0.018 (0.174)	**<0.001**
Femur	[0;4]	0.149 (0.538)	-	-	-

Then, we synthesized the minimum number of fractures by a new scoring: 0: absence of fracture, 1: single fracture, and 2: more than two fractures.

Single fractures are more widespread in fall cases than in blow cases (Table *7*, Figure 39).

Fall cases exhibited widespread simple fractures with close frequencies (between 1.28 and 8.51%), even for the face which presents 12.77% of fractures and the basicranium, 12.77% (Table *7*, Figure 39).

In blow cases, only five anatomical skeletal regions are concerned by simple fractures, with a frequency higher than 1%: the basicranium (10.30%, *n*=17), the cranial vault (2.42%, *n*=4), the face (16.97%, *n*=28), the mandible (19.39%, *n*=32) and lumbar vertebrae (2.42%, *n*=4) (Table *7*, Figure 39).

Fractures of the basicranium occurred more frequently in falls (12.77%, *n*=30) than in blows (10.30%, *n*=17) (Table *7*, Figure 39).

Table 7: Number of fractures recorded in 3 stages present in the anatomical region, in both etiologies (p value of fisher's exact test; in bold: significant values)

	Falls (n=235)				Blows (n=165)				*p* value
	Simple (n)	Multiple (n)	Simple (%)	Multiple (%)	Simple (n)	Multiple (n)	Simple (%)	Multiple (%)	
Basicranium	30	33	12.77	14.04	17	19	10.30	11.52	0.529
Cranial Vault	20	26	8.51	11.06	4	12	2.42	7.27	**0.012**
Face	30	42	12.77	17.87	28	66	16.97	40.00	**<0.001**
Mandible	4	10	1.70	4.26	32	32	19.39	19.39	**<0.001**
Clavicle	3	6	1.28	2.55	0	0	0.00	0.00	**0.018**
Scapula	13	14	5.53	5.96	1	0	0.61	0.00	**<0.001**
Sternum	12	3	5.11	1.28	0	0	0.00	0.00	**<0.001**
Ribs	7	56	2.98	23.83	0	5	0.00	3.03	**<0.001**
Cervical V.	5	9	2.13	3.83	0	0	0.00	0.00	**0.002**
Thoracic V.	16	31	6.81	13.19	1	2	0.61	1.21	**<0.001**
Lumbar V.	17	65	7.23	27.66	4	4	2.42	2.42	**<0.001**
Sacrum	16	33	6.81	14.04	0	0	0.00	0.00	**<0.001**
Coxal	12	42	5.11	17.87	1	1	0.61	0.61	**<0.001**
Femur	10	10	4.26	4.26	0	0	0.00	0.00	**<0.001**

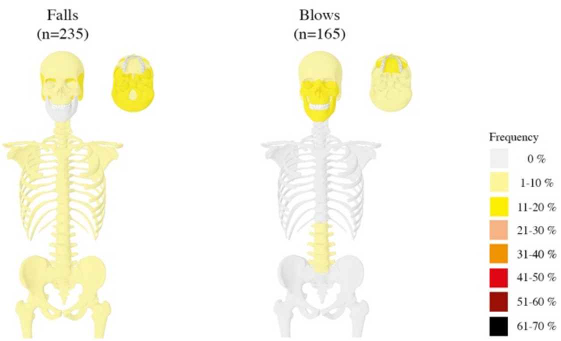

Figure 39: The frequency and distribution of simple fractures related to the etiology

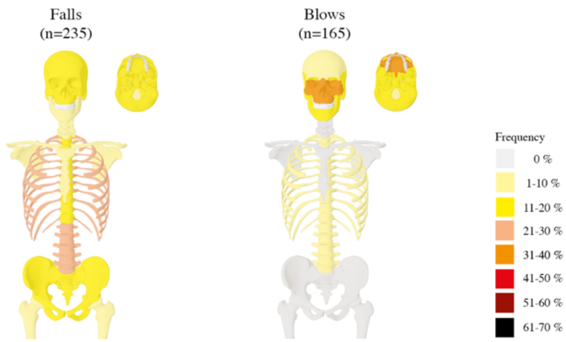

Figure 40: The frequency and distribution of multiple fractures related to etiology

Falls cases exhibited again widespread multiple fractures (Table *7*, Figure 40). Multiple fractures are more frequent in lumbar vertebrae (27.66%, *n*=65), then by decreasing frequency in ribs (23.83%, *n*=56), face and coxal (17.87%, *n*=42; for both), sacrum, and basicranium (14.04%, *n*=33; for both), the mandible is more concerned by multiple fractures (4.26%, *n*=10) than simple ones (Table *7*, Figure 40).

Multiple fractures in blows are more localized and involved seven anatomical regions with a frequency higher than 1%: the face (40%, *n*=66), the mandible (19.39%, *n*=32), the basicranium (11.52%, *n*=19), the cranial vault (7.27%, *n*=12), the ribs (3.03%, *n*=5), the lumbar vertebrae (2.42%, *n*=4) and the thoracic vertebrae (1.21%, *n*=2). No multiple fractures were observed on the clavicle, scapula, sternum, cervical vertebrae, sacrum, and femur (Table *7*, Figure 40).

A decision tree was built to identify the criteria playing a key role in the distinction between blows and falls. For this purpose, the number of fractures according to the three stages in fourteen anatomical regions were used as independent variables of the model. The decision tree of our study integrated all 400 cases.
The three variables identified by the decision tree were the number of fractures on the mandible, on the face, and on the cranial vault. For each branch, the numbers of falls and blows are indicated (Figure 41). Given that 28 cases of blows and 54 cases of falls were misclassified, the misclassification rate with the leave-one-out method was equal to 19.5%.
Therefore, the decision tree correctly classified 80.5% of the total cases (77.02% of falls and 83.03% of blows). Perfect discrimination remains unrealistic, but the decision tree shows a strong discrimination potential between fall and blow cases using the number of fractures on the mandible, face, and cranial vault.

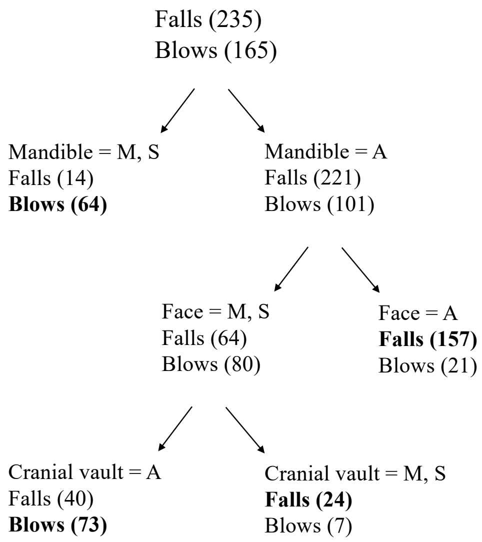

Figure 41: Decision Tree (A: no fracture, S: simple fracture, M: multiple fractures)

1.4. Discussion

1.4.1. Repeatability

The results showed a perfect and substantial agreement for all the variables.

1.4.2. Fracture location, sex, and age

The presence of fractures by anatomical region, by sex and age (Table *5*) showed that face fractures are found significantly more often in males. This is consistent with literature and with our sample distribution by sex and etiology where males represent more than 90% of blow cases (Figure 36), and with the fact that there is a significant tendency for face fractures to be caused by blows (Table *4*) (Abosadegh & Rahman, 2018; Brook & Wood, 1983; Redfern, 2017). Concerning the thoracic and lumbar vertebrae, as well as the coxal and sacrum, there is a statistically significant difference showing that these bones are more often fractured in women (Table *5*). Once again, this appears to be consistent with the fact that these bones are more often fractured in case of falls (Table *4*) and that there is almost three times more women in our sample affected by falls (Figure 36). This prevalence of fracture can be explained by differences in bone structure between the sexes (influenced, among other things, by osteoporosis, pregnancy or lactation) (Burke, 2012; Lapina & Tiškevičius, 2014; Levine, 2009; Sidon *et al.*, 2018; Timsit, 2005). Finally concerning age, Table 5 showed that the mandible is significantly less fractured when age increases, and this makes sense with the fact that mandible fracture is associated with blows (Table 4) and blows decreases with age (Figure 37) (Ahmed *et al.*, 2018; Atilgan *et al.*, 2010; Beaumont *et al.*, 1985; Ghodke *et al.,* 2013; Kansakar *et al.*, 2017; Lee, 2009; Sojat *et al.*, 2001; Walker, 2001; Zaleckas *et al.*, 2013). On the contrary, Table *5* shows that ribs and lumbar vertebrae are significantly more often fractured with increasing age, and these bone fractures are associated with falls (Table *4*) which increase with age (Figure 39)(Agnew *et al.*, 2013; Talbot *et al.*, 2005).

1.4.3. Skeletal fractures: circumstances, incidence, topography

In this study, fractures occurred more frequently in falls for the postcranial skeleton, the basicranium and the cranial vault. Conversely, the fractures of the face and the mandible were more frequently found in blows.

Falls

In fall cases, males are more frequent (80.85%, *n*= 190) than females (19.15%, *n*= 45) and the number of falls increases with age. Indeed, 43.83% of the population aged between 40-49 years (*n*= 103) compared to 28.51% of individuals aged 20 to 29 (*n*= 67).

These observations enabled us to highlight those fractures are more frequent and better distributed over the skeleton in fall cases. According to Kratter, falls cannot cause injuries of the vertex area nor the cranial vault (above the line binding the frontal eminence, the parietal eminence, and the external occipital protuberance), except in the case of a fall from a height or an impact against an edge or a corner (Fracasso *et al.*, 2011; Geserick *et al.*, 2014).

Simple fractures (i.e. single fractures) are more common in the face (12.77%, *n*=30) and the base of the skull (12.77%, *n*=30).

Multiple fractures are rather well distributed on the skeleton, even if they present a lower frequent localization compared to the ribs (23.83%, *n*=56) and the lumbar vertebrae (27.66%, *n*=65).

The minimum number of fractures on the scapula, ribs, coxal bone, thoracic, and lumbar vertebrae is significantly more critical in falls. These results are perfectly consistent with the literature (Burke, 2012; Cooper *et al.*, 1995; Cooper *et al.*, 1993; Court-Brown, 2015; Fracasso *et al.*, 2011; Hsu *et al.*, 2003; Meldon & Moettus, 1995; Richter *et al.*, 1996; Samuels & Kerstein, 1993; Wedel & Galloway, 2014).

Blows

In blow cases, males are more frequent (92.12%, *n*= 152) than females (7.88%, *n*= 13) and the number of blows decreases with age. Indeed, 46.67% of individuals aged 20-29 years have at least one fracture (*n*= 77) compared to 20% of individuals aged 40 to 49 (*n*= 33). In 2001, Walker noted that people involved in assaults tend to be young males (Walker, 2001).

Fractures on the skeleton are located on the face (64.24%, *n*= 106) and the mandible (38.79%, *n*= 64).

Simple fractures show prevalence for the same anatomical regions, presenting respectively 16.97% (*n*= 28) and 19.39% (*n*= 32).

Multiple fractures are more frequent in the face (40%, *n*= 66), mandible (19.39%, *n*= 32) and basicranium (11.52%, *n*= 19).

The minimum number of fractures on the face and the mandible is significantly higher in blows. These results are concordant with the literature since the head and face are the main rage focus of the perpetrator because these areas are psychologically linked to the victim's identity (Henn & Lignitz, 2004; Shepherd *et al.*, 1987; Strauch *et al.*, 2001; Wedel & Galloway, 1999).

However, our results are divergent from Kratter who showed that blows can cause injury in every region of the head with the exception of the base of the skull (Fracasso *et al.*, 2011; Geserick *et al.*, 2014).

Cranial Vault

Our results showed that fractures in the cranial vault occurred more frequently in fall cases (20%, *n*=47) than in blows (9.70%, *n*=16).

Many studies showed that fractures and injuries on the cranial vault and above the HBL could not result from falls, except in cases of repeated falls, falls from a height or an impact against an edge or a corner; so they would be less frequent than in blow cases (Ehrlich & Maxeiner, 2002; Fracasso *et al.*, 2011; Geserick *et al.*, 2014; Guyomarc'h *et al.*, 2010; Kremer *et al.*, 2008; Kremer & Sauvageau, 2009; Maxeiner & Ehrlich, 2000; Walcher, 1931). However, our results show the opposite.

Basicranium

Our results showed that fracture on the basicranium occurred more frequently in fall cases (26.81%, *n*=63) than in blow cases (21.82%, *n*=36).

According to Kratter (*in* Fracasso *et al.*, 2011), blows can cause injury in every region with the exception of the base of the skull. However, Rogers (1992) wrote that basilar skull fractures could result indirectly from blows to the front of the head or through compression of the spine against the base of the skull. Our results confirm these latest findings.

Face

Our results showed that fractures in the face occurred more frequently in blow cases (64.24%, *n*=106) than in falls (33.62%, *n*=79). Concerning blow cases, this result is concordant with those of many authors who said that one of the most commonly sustained injuries is to the face (Redfern, 2017; Walker, 2001).

According to Arabion *et al.* (Arabion *et al.*, 2014), the most frequent etiology of facial fractures is falling while for other studies, it is traffic-related (Abosadegh & Rahman, 2018; Ansari, 2004; Arabion *et al.*, 2014; Chrcanovic *et al.*, 2004; Van Den Bergh *et al.*, 2012). However, based on the study of Guyomarc'h *et al.* (2010), one of the criteria pointing toward blows is the presence of facial fractures. Several authors agree, showing that violence is the most frequent cause of craniofacial fractures, and our results are consistent with this. Our results showed that adult males are more frequently implied, whatever the etiology (Abosadegh & Rahman, 2018; Brook & Wood, 1983; Redfern, 2017).

Mandible

Fractures on the mandible occur in 38.79% (*n*=64) of blow cases and 5.96% (*n*=14) of fall cases. Our results are similar to those of many studies showing that most fractures were caused by assault followed by falls (Beaumont *et al.*, 1985; Lee, 2009; Sojat *et al.*, 2001; Zaleckas *et al.*, 2013) and are more frequent in young males (20-30 years old) (Ahmed *et al.*, 2018; Atilgan *et al.*, 2010; Ghodke *et al.*, 2013; Kansakar *et al.*, 2017).

Clavicle

Clavicle fractures were only observed in fall cases (3.83%, *n*=9) with a predominance in males. These results are concordant with the literature. Clavicle fractures occur from sports, falls, and motor vehicle accidents (Burke, 2012; Court-Brown, 2015; Dias & Gregg, 1991; Robinson, 1998; Saukko & Knight, 2016). According to Sirin *et al.* (Aydin & Topkar, 2018), this injury occurs more frequently in males than in females, with the highest incidence in the 20- to 30-year-old age group, which is similar to our study.

Scapula

Scapula fractures occur in 11.49% (*n*=27) in fall cases and 0.61% (*n*=1) in blows with a predominance in people aged 40 and 49 years (10.29%, *n*=14). According to the literature, scapula fractures are uncommon and result from falls or motor vehicle incidents (Burke, 2012; Court-Brown, 2015; Wedel & Galloway, 2014). People aged 40 to 60 years are more implied, which is concordant with our results (Burke, 2012; Neer, 1984; Wedel & Galloway, 2014).

Rib

In our study, rib fractures are more frequent in fall cases (26.81%, *n*=63) than in blow cases (3.03%, *n*=5). People aged 40 and 49 years are more implied by this type of fracture.

According to the literature, rib fractures are common injuries and result from sport (stress fractures) and minor injuries (especially in elderly individuals) (Barrett-Connor *et al.*, 2010; Talbot *et al.*, 2017) or from homicidal actions, particularly stomping on the chest of a prone victim or a direct blow or kicking, and from cardiopulmonary resuscitation (Kim *et al.*, 2013; Saukko & Knight, 2016). Fractures in the upper zone of the thoracic cage (one to fourth ribs) require high-velocity trauma (Talbot *et al.*, 2017). Rib fractures are complex and are an essential indicator of trauma severity (morbidity and mortality increase with increasing numbers of ribs fractured) (Kani *et al.,* 2019; Restrepo *et al.*, 2009; Senekjian & Nirula, 2017; Talbot *et al.*, 2017).

Sternum

In our sample, sternum fractures only occur in fall cases (6.38%, *n*=15). According to the literature, sternal fractures can result from motor vehicle accidents, contact sports, falls, and assaults (Kani *et al.*, 2019; Khoriati *et al.*, 2013; Restrepo *et al.*, 2009).

Vertebrae

In our sample, there are no cervical fractures in blows, but in falls they have a frequency of 5.96% (*n*=14).

Overall, spinal fractures frequently occur in falls (Court-Brown, 2015). Cervical fractures are frequent in motor vehicle accidents, sporting accidents, and assaults with weapons (Burke, 2012). During an attack, these kinds of fractures are more due to the fall (Eskesen *et al.*, 2018; Kulvatunyou *et al.*, 2011; Rhee *et al.*, 2006).

In our sample, fractures on thoracic and lumbar vertebrae are more frequent in fall cases than in blows.

According to the literature, thoracolumbar injuries are due to motor vehicle accidents and fall from a significant height (Burke, 2012; Cooper *et al.*, 1995, 1993; Hsu *et al.*, 2003; Meldon & Moettus, 1995; Richter *et al.*, 1996; Samuels & Kerstein, 1993).

The thoracolumbar fractures are more frequent in females. These significant differences between males and females can be explained by structural and kinetic differences, “probably an evolutional allowing female to carry their fetus while standing in an upright position” (Sidon *et al.*, 2018). Indeed, females display a lumbar hyper lordosis, a thoracic hypokyphosis and a lesser lumbar range of motion in flexion-extension (Sidon *et al.*, 2018). These elements limit the prevalence of cervical spine fracture and can be the cause of lumbar spine fractures in females. Moreover, according to many authors, during pregnancy and lactation, females lose 3% to 10% of trabecular bone (Kovacs, 2011).

Sacrum

Our results show that sacral fractures only occur in fall cases (20.85%, *n*= 49) and are more frequent in females (28.89%, *n*=13).

According to the literature, fractures of the sacrum can be caused by a stress fracture or insufficiency fracture (Nusselt *et al.*, 2010; Rogers, 1992). This last fracture occurs within normal stress on the bone. The bone can be weakened by pregnancy and lactation, radiation therapy, rheumatoid arthritis, osteoporosis (which can also be caused by some medications or diseases), demineralization in elderly patients and postmenopausal females (Burke, 2012; Lapina & Tiškevičius, 2014; Levine, 2009; Timsit, 2005). Sacral fracture frequently occurs in motor vehicle accidents and falls, and are more frequent in females (Bydon *et al.*, 2014; Denis *et al.*, 1988; Meredith *et al.*, 2013; Rodrigues-Pinto *et al.*, 2017; Sabiston & Wing, 1986).

Coxal Bone

In our study, fractures of the coxal bone are more frequent in falls (22.98%, *n*=54) and in females (31.11%, *n*=14).

Pelvic fractures in adults are associated with significant morbidity and mortality (Biffl *et al.*, 2001; Wedel & Galloway, 2014). Pelvic fractures are most common in young adult males and older males and females (Chien *et al.*, 2010; Ragnarsson & Jacobsson, 1992). The prevalence of pelvic fractures is male for Pereira *et al.* (2017) and female for Buller *et al.* (2016), Sanders *et al.* (1999), Melton *et al.* 1981 (1981). According to Balogh *et al.* (2007), pelvic fractures in males occur more frequently in high-energy accidents (motor vehicle accidents) and females in low-energy injuries (Balogh *et al.*, 2007). Pelvic fractures are common in motor vehicle accidents, falls, and sport-related accidents (Burke, 2012; Court-Brown, 2015; Wedel & Galloway, 2014).

Femur

This study shows that fractures of the proximal femur only occur from falls (8.51%, *n*=20).

As for the coxal bone and sacrum, insufficiency fractures can occur on the proximal extremity of the femur (Park *et al.*, 2011). In young adults, femur fractures result from motor vehicle accidents, falls from heights or sports (Burke, 2012; Court-Brown, 2015; Hollis *et al.,* 2015; Wedel & Galloway, 2014).

1.4.4. The skull : an important anatomical region in the distinction between falls and blows?

A significant amount of research has been devoted to understanding the biomechanics of fractures by powerful forces (Kieser *et al.*, 2009; Kroman, 2007; Reber & Simmons, 2015) but few studies have focused on the evaluation of the origin of the trauma by analyzing the fracture location and morphology (Ehrlich & Maxeiner, 2002; Guyomarc'h *et al.*, 2010; Kremer *et al.*, 2008; Kremer & Sauvageau, 2009; Marinho & Cardoso, 2016; Maxeiner & Ehrlich, 2000; McNulty, 2016; Moraitis *et al.*, 2009; Sharkey *et al.*, 2011). This is why it is necessary to deepen our knowledge in this field. Blunt force injuries located in the cranium and in the trunk are preferentially associated with interpersonal violence. They are often linked with the manner and cause of death which make their examination of crucial importance in the medicolegal investigation of death circumstances (Ambade & Godbole, 2006; Arbes & Berzlanovich, 2015; Freeman *et al.*, 2014; Henn & Lignitz, 2004; McNulty, 2016; Preuß *et al.*, 2004; Shepherd *et al.*, 1987; Sterzik *et al.*, 2016; Strauch *et al.*, 2001).

One of the first authors who tried to distinguish between falls and blows based on the skull lesions was Richter (1905b). He highlighted the attention that must be paid to the amount of skin bruises and their location. If there are reasons for repeated falls, if the bruises are numerous and located in regions that cannot be involved in cases of a fall (the cranial vertex); we can hypothesize that the child is beaten.

In 1921, Kratter's researches (as cited by Fracasso in 2011) showed falls can cause injuries to the vertex area and cranial vault when the fall is from a great height or if there is impact with an obstacle during the fall (Fracasso *et al.*, 2011; Geserick *et al.*, 2014).

Regarding a similar line, Walcher (1931), created the Hat Brim Line (HBL) rule which says that fall-related injuries do not lie above the hat brim line when some conditions are fulfilled (standing position of the individual before falling, flat floor without incline or stairs, falling from one's height, absence of intermediate obstacles) but the rule is not applicable for small children (Geserick *et al.*, 2014).

Nowadays, the HBL is defined as the area above the Frankfort horizontal plane, located between the line passing through the glabella (G-line) and the line passing through the center of the external auditory meatus (EAM-line) (Kremer *et al.*, 2008) (Figure 42).

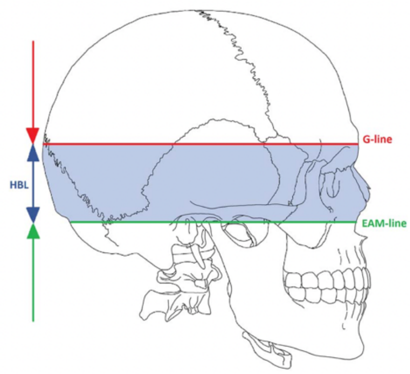

Figure 42: HBL (modified from Kranioti, 2015, p30)

The use of the Hat Brim Line rule in the distinction between falls and blows is controversial. Despite this, some studies have used this rule when observing skull fractures and skin lesions. The few studies that have compared falls and blows cases in relation to the HBL to determine the validity of this rule are those cited below.

Ehrlich and Maxeiner, Kremer *et al.*, and Guyomarc'h *et al.* undertook studies to distinguish between falls and blows in blunt head traumas (Ehrlich & Maxeiner, 2002; Guyomarc'h *et al.*, 2010; Kremer *et al.*, 2008; Kremer & Sauvageau, 2009; Maxeiner & Ehrlich, 2000). Ehrlich and Maxeiner studied 254 falls (203 on a flat surface, 51 downstairs) and 51 blows (Ehrlich & Maxeiner, 2002; Maxeiner & Ehrlich, 2000). They observed that lacerations from blows occur more often above the HBL (55%) than lacerations from falls (33%).

Kremer *et al.* focused on the location of cranial fractures and number of lacerations (Kremer *et al.*, 2008; Kremer & Sauvageau, 2009). In Kremer *et al.* (2008), 36 falls (23 from one's own height, 13 downstairs), and 44 blows were observed. The results show that injuries from blows are more often found above HBL, although this rule should be used with caution. In Kremer *et al.* (Kremer & Sauvageau, 2009), 50 falls were observed (29 from one's height, 21 downstairs) and 64 interpersonal violence with a blunt weapon. The study confirms that injuries inflicted by blows are often situated above HBL, a laceration inside HBL is more in favor of a fall (66.7%), and a skull fracture inside HBL is found equitably in both etiologies.

Guyomarc'h *et al.* (2010) describe the number and length of lacerations on the entire skull, type of skull fractures, location of injuries and the presence or the absence of postcranial injury in 50 cases of falls (29 from own height, 21 downstairs) and 63 cases of homicidal blows. The results show a strong discrimination potential between fall and blow cases with four criteria including the presence of fractures above the HBL (in favor of blows).

The authors confirmed that HBL must be used carefully and not as a single criterion in the distinction between falls and blows. Perfect discrimination remains unrealistic, and before we can quickly and accurately distinguish falls from blows, there is a lot more work to be performed. Moreover, we must be careful as some studies have a weak sample.

Besides, we find more fractures related to falls than to blows above this HBL so the use of the Hat Brim Line rule is limited. In both cases, the face is the anatomical region of the skull more frequently touched by fractures. Concerning the basicranium, the frequency of occurrence of fractures is similar in both etiologies. Finally, the presence of fractures on the mandible is an important element to strengthen the hypothesis of blows struck at the individual.

The decision tree proposed in our study showed the importance of fractures located on the mandible, on the face and on the cranial vault because it allows a distinction between blows and falls. By using this tree on our study sample to predict the etiology of fractures and taking care to use a “leave one out” (LOO) procedure, the decision tree correctly classified 80.5% of the cases.

Some of these anatomical regions were already used in the "combined criteria tools" of Guyomarc'h *et al.* (2010) which considered the number of scalp lacerations, the scalp laceration length, the vault fracture type, and the presence or absence of facial fractures. Their decision tree classified 82% of falls and 93.7% of blows correctly.

However, it should be noted that these two studies did not consider certain parameters that can affect bone fractures (such as one's character or region). Indeed, some authors have shown that the risk of fracture and their location are related to ethnicity (De Silva & Rose, 2011; Popp *et al.*, 2017; Villa *et al.*, 2001).

2. The distinction between blows and falls by pattern and morphology of fractures

The obtained data will be used to publish an original paper

2.1. Introduction

In collaboration with the pathologist, one of the tasks of the forensic anthropologist is to analyze and interpret skeletal trauma to bring information about the circumstances of death (Kranioti, 2015; Passalacqua & Fenton, 2012).

Blunt force trauma (BFT) is complicated and difficult to interpret because of its variability. It can be caused by a blunt object or a surface, as in transportation fatalities, falls, or interpersonal violence (Ambade & Godbole, 2006; Sterzik *et al.*, 2016; Wedel & Galloway, 2014).

BFT is one of the most common injuries encountered, so distinguishing between falls and blows is essential (Kranioti, 2015; Kremer & Sauvageau, 2009). The Hat Brim Line rule (HBL) has often been used to differentiate both etiologies (Ehrlich & Maxeiner, 2002; Guyomarc'h *et al.*, 2010; Kremer & Sauvageau, 2009; Maxeiner & Ehrlich, 2000). Nevertheless, this method is not used as it should be and do not follow Daubert's rules allowing a methodology can be presented as evidence in court (Lesciotto, 2015).

This study aims to investigate whether circumstances of traumatic events influence the morphology and pattern of fractures they create on the skeleton (skull and trunk).

2.2. Material and methods

2.2.1. Study sample

A retrospective review of post-traumatic patients who underwent CT scans between 2008 and 2019 found 400 falls and blows with at least one fracture. These anonymized CT scans were performed at the Marseille Public Hospital Support Center (AP-HM, France), Coimbra University Hospital Center, and Nancy Regional Hospital Center and collected from the PACS (Picture Archive and Communication System). Full-body scans are rarely needed so CT scans were viewed in two parts: cranium and mandible on one side, from the first cervical to the pelvis, without the appendicular skeleton on the other.

According to the acquisition protocol, the scanner slices were 0.6 mm and 1.25 mm thick. We selected adults between the ages of 20 and 49 to have homogeneity in the physicochemical properties of the bone.

We reviewed medical information and case details related to the circumstances that caused the BFT for each of these cases. As this is a retrospective study based on the clinical management of patients, not all information regarding fracture status is presented systematically. Therefore, there is no data on the number of perpetrators or blows in the case of impact injuries. The characteristics of the individuals were recorded. Details included the following data :

Circumstances of blunt force trauma:

- Date of the traumatic event
- Type of blunt force trauma (falls or blows)
- Date of CT scan
- Height of the fall (when the medical report gives this information)
- Blunt force object used (when the medical report gives this information)

Characteristics of the individuals:

- Age
- Sex

All individual patient data are anonymized in accordance with the standards of the National Ethics Committee for Health and Life Sciences (CCNE), the National Council for Ethics of Life Sciences (CNECV) and the 1975 Declaration of Helsinki on personal privacy and confidentiality. data. All that was known about each subject was age, sex, and examination date.

2.2.2. Variables

We selected 372 types of fractures. We used two classifications, the AO/OTA and the one presented by Galloway and Wedel (2014) (Marsh *et al.*, 2007). A binary score (0 absent/1 present) was used to assess the presence of fractures in each bone. All variables totally absent from the sample have been deleted, thus reducing the type of fracture to 246.

The observations were done using multiplanar reconstructions (MPR), maximum intensity projection (MIP) and volume rendering (VR) reconstructions on AW Workstation (AW server 2.0, GE HealthCare, Milwaukee, US) and Horos (version 3.3.5®, © 2021 Horos Project).

2.2.3. Statistical analyses

Fisher's exact test was used to identify associations between two qualitative variables, particularly between fractures and gender or age group or context. Then, we used the Mean Measure of Divergence (MMD), the most common method of calculating the distance (the mean variance) from a set of non-metric features evaluated in binary scoring (Corruccini, 1974;

Sjøvold, 1973, 1977). MMD values greater than double their respective standard deviation are deemed statistically significant, indicating that the compared samples differ.

A decision tree was built to predict the etiology of these fractures (falls/blows).

We used the R Software® version 3.3.2 (R Foundation for Statistical Computing, Vienna, Austria) to perform statistical analyses. The significant level used for all tests was 0.05. We used {AnthropMMD} R package to calculate the distance between the 2 etiologies regarding fractures. {rpart} R package was used to build the decision tree.

2.3. Results

2.3.1. Characteristics of the sample

Our sample is composed by 235 falls and 165 blows from three hospitals. The sample distribution by sex for each aetiology is shown in Figure 43 and by age groups in Figure 44.

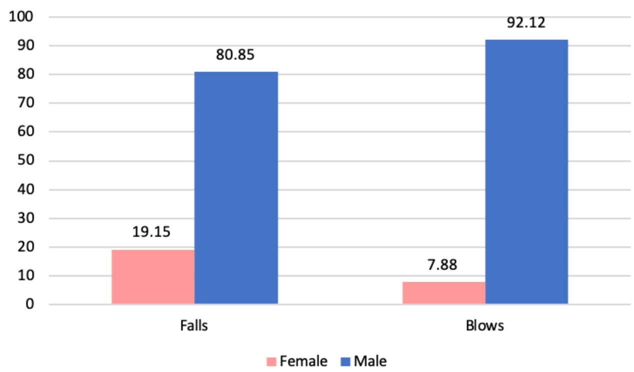

Figure 43: Distribution of the sample by sex for each etiology

We observed 190 males (80.85%) and 45 females (19.15%) in fall cases, and 152 males (92.12%) and 13 females (7.88%) in blow cases.

Fisher's exact test shows that the proportion of males significantly differs between the two etiologies (p=0.001).

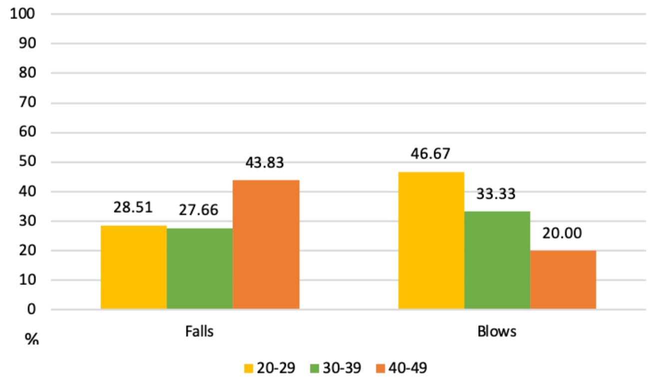

Figure 44: Distribution of the sample by age for each etiology

Adults 40-49 years old involved in falls are more frequent (43.83%) than the two other age groups (27.66 % for individuals between 30 and 39 years; 28.51% for the group 20-29 years) (Figure 44).

Adults 20-29 years old involved in blows are more frequent (46.67%) than the two other age groups (33.33 % for individuals between 30 and 39 years; 20% for the group 40-49 years) (Figure 44).

Fisher's exact test shows a significant difference in the distribution of the individuals by age group between the two etiologies ($p<0.001$).

2.3.2. Skeletal fracture morphology and pattern

There were 246 different fracture morphologies that resulted from falls and blows. We tested them according to age, sex, and etiology.

Comminuted fracture of the maxilla, fracture of the body and mixed fracture of the mandible, linear fracture of the occipital, mixed fracture of the 3rd, 4th, and 6th ribs, fracture of the anterior arch of the 5th and 7th ribs, fracture of the posterior arch of the 9th, 10th and 11th ribs, and fracture of the transverse process of the 12th thoracic vertebrae were significantly associated with age Table 8.

Table 8: Morphology of fractures by etiology and age (p value associated with the Fisher's exact test; in bold: significant values)

	20-29		30-39		40-49		*p value*
	n	%	n	%	n	%	
Comminuted fracture of the maxilla (MA5)	30	20.83	22	18.33	13	9.56	**0.02**
Fracture of the body of the mandible (MD3)	12	8.33	2	1.67	1	0.74	**0.002**
Mixed fractures of the mandible (MD5)	9	6.25	4	3.33	2	1.47	**0.11**
Linear fracture of the occipital bone (O1)	1	0.69	7	5.83	6	4.41	**0.04**
Mixed fractures on the 3rd rib (R3.5)	0	0.00	1	0.83	5	3.68	**0.02**
Mixed fractures on the 4th rib (R4.5)	0	0.00	1	0.83	6	4.41	**0.008**

Anterior arch fracture in the 5th rib (R5.1)	0	0.00	2	1.67	5	3.68	**0.04**
Mixed fractures on the 6th rib (R6.5)	0	0.00	2	1.67	5	3.68	**0.04**
Anterior arch fracture in the 7th rib (R7.1)	0	0.00	2	1.67	6	4.41	**0.02**
Posterior arch fracture in the 9th rib (R9.3)	2	1.39	1	0.83	9	6.62	**0.02**
Posterior arch fracture in the 10th rib (R10.3)	1	0.69	4	3.33	10	7.35	**0.01**
Posterior arch fracture in the 11th rib (R11.3)	0	0.00	3	2.50	9	6.62	**0.002**
Transverse process of the 12th thoracic vertebrae (VT12.5)	0	0.00	1	0.83	5	3.68	**0.02**

Comminuted fractures of the maxilla, fracture of the body, and mixed fracture of the mandible occurred more frequently in individuals aged between 20 and 29 years (Table 8).
Linear occipital fracture was more frequent in individuals 30-39 years old (Table 8).
Mixed fracture of the 3rd, 4th, and 6th ribs, fracture of the anterior arch of the 5th and 7th ribs, fracture of the posterior arch of the 9th, 10th, and 11th ribs, and fracture of the transverse process of the 12th thoracic vertebrae occurred more frequently in individuals aged between 40 and 49 years (Table 8).

Linear fracture of the occipital, mixed fracture of the 7th lumbar vertebrae, and comminuted fracture of the coxal bone and sacrum were significantly associated with sex (Table 9).

Table 9: Morphology of fractures by etiology and sex (p value associated with the Fisher's exact test; in bold: significant values)

	Female		Male		*p value*
	n	%	n	%	
Linear fracture of the occipital (O1)	5	8.62	9	2.63	**0.04**
Comminuted fracture of the coxal bone (PG.1C6)	11	18.97	23	6.73	**0.005**
Comminuted fracture of the sacrum (SAC6)	8	13.79	18	5.26	**0.04**
Mixed fractures of the lumbar vertebrae (VL1.7)	3	5.17	1	0.29	**0.01**

All the types of fractures presented in Table 9 were more frequent in females than males.

We observed that 51 fracture morphologies are significant between both etiologies. Linear fracture on the frontal bone, fracture of the sphenoid's body, middle arch fracture of the 7th rib, posterior arch of the 8th, 10th, 11th and 12th ribs, fracture of the spinous process of the 7th cervical vertebrae, compression of the 1st lumbar vertebrae, fracture of the transverse process of the 1st, 2nd, 3rd and 4th lumbar vertebrae, comminuted fracture of the coxal bone, and juxta-articular/articular fracture of the sacrum occurred more frequently on falls than blows (Table 10).
Types of fracture only present in fall cases are:

- comminuted fractures of the frontal bone, scapula, sacrum, and femur trochanter
- oblique/backward angulation fracture of the body of the sternum
- posterior arch fracture of the 1st, 2nd, 3rd, 4th, 5th, 6th, 7th, and 8th ribs
- mixed fractures of the 2nd and 3rd ribs, 1st lumbar vertebrae and coxal bone
- middle arch fracture of the 5th and 6th ribs
- anterior arch fracture of the 7th rib
- fracture do the spinous process of the 7th cervical vertebrae
- compression of the 11th thoracic vertebrae, 2nd, and 4th lumbar vertebrae
- fracture of the transverse process of the 11th and 12th thoracic vertebrae and 5th lumbar vertebrae
- fracture of the 1st lumbar vertebrae and coccyx

Table 10: Morphology of fractures by aetiology (p value associated with the Fisher's exact test; in bold: significant values)

	Falls		Blows		*p value*
	n	%	n	%	
Linear fracture of the frontal bone (F1)	17	7.23	2	1.21	**0.007**
Comminuted fracture of the frontal bone (F6)	10	4.26	0	0.00	**0.006**
Fracture of the body of the sphenoid (SC)	21	8.94	6	3.64	**0.04**
Comminuted fracture of the maxilla (MA5)	30	12.77	35	21.21	**0.03**
Fracture of the nasal bone (N)	36	15.32	32	19.39	**0.04**
Comminuted fracture of the scapula (SCP6)	14	5.96	0	0.00	**<0.001**
Oblique/backward angulation fracture of the body of the sternum (STC3)	7	2.98	0	0.00	**0.04**
Posterior arch fracture in the 1st rib (R1.3)	6	2.55	0	0.00	**0.04**
Posterior arch fracture in the 2nd rib (R2.3)	7	2.98	0	0.00	**0.04**
Mixed fractures on the 2nd rib (R2.5)	6	2.55	0	0.00	**0.04**
Posterior arch fracture in the 3rd rib (R3.3)	8	3.40	0	0.00	**0.02**
Mixed fractures on the 3rd rib (R3.5)	6	2.55	0	0.00	**0.04**
Posterior arch fracture of the 4th rib (R4.3)	6	2.55	0	0.00	**0.04**
Middle arch fracture of the 5th rib (R5.2)	8	3.40	0	0.00	**0.02**
Posterior arch fracture in the 5th rib (R5.3)	8	3.40	0	0.00	**0.02**
Middle arch fracture of the 6th rib (R6.2)	7	2.98	0	0.00	**0.04**
Posterior arch fracture in the 6th rib (R6.3)	10	4.26	0	0.00	**0.006**
Anterior arch fracture in the 7th rib (R7.1)	8	3.40	0	0.00	**0.02**
Middle arch fracture of the 7th rib (R7.2)	11	4.68	1	0.61	**0.02**
Posterior arch fracture in the 7th rib (R7.3)	8	3.40	0	0.00	**0.02**
Posterior arch fracture in the 8th rib (R8.3)	15	6.38	1	0.61	**0.003**
Posterior arch fracture in the 9th rib (R9.3)	12	5.11	0	0.00	**0.002**
Posterior arch fracture in the 10th rib (R10.3)	14	5.96	1	0.61	**0.006**
Posterior arch fracture in the 11th rib (R11.3)	11	4.68	1	0.61	**0.02**
Posterior arch fracture in the 12th rib (R12.3)	11	4.68	1	0.61	**0.02**
Spinous process of the 7th cervical vertebrae VC7.3	7	2.98	0	0.00	**0.04**

Compression of the 11th thoracic vertebrae (VT11.2)	7	2.98	0	0.00	**0.04**
Fracture of the transverse process of the 11th thoracic vertebrae (VT11.5)	6	2.55	0	0.00	**0.04**
Fracture of the transverse process of the 12th thoracic vertebrae (VT12.5)	6	2.55	0	0.00	**0.04**
Fracture of the 1st lumbar vertebrae (VL1.1)	10	4.26	0	0.00	**0.006**
Compression of the 1st lumbar vertebrae (VL1.2)	11	4.68	1	0.61	**0.02**
Fracture of the transvers process of the 1st lumbar vertebrae (VL1.5)	27	11.49	3	1.82	**<0.001**
Mixed fractures of the 1st lumbar vertebrae (VL1.7)	10	4.26	0	0.00	**0.006**
Compression of the 2nd lumbar vertebrae (VL2.2)	8	3.40	0	0.00	**0.02**
Fracture of the transvers process of the 2nd lumbar vertebrae (VL2.5)	34	14.47	3	1.82	**<0.001**
Fracture of the transvers process of the 3rd lumbar vertebrae (VL3.5)	35	14.89	4	2.42	**<0.001**
Compression of the 4th lumbar vertebrae (VL4.2)	6	2.55	0	0.00	**0.04**
Fracture of the transvers process of the 4th lumbar vertebrae (VL4.5)	30	12.77	2	1.21	**<0.001**
Fracture of the transvers process of the 5th lumbar vertebrae (VL5.5)	17	7.23	0	0.00	**<0.001**
Comminuted fracture of the sacrum (SAC6)	26	11.06	0	0.00	**<0.001**
Juxta-articular/articular fracture of the sacrum (SAC3)	12	5.11	1	0.61	**0.001**
Fracture of the coccyx (VCO)	6	2.55	0	0.00	**0.04**
Comminuted fracture of the coxal bone (PG.1C6)	33	14.04	1	0.61	**<0.001**
Mixed fracture of the coxal bone (PG.1C7)	9	3.83	0	0.00	**0.01**
Comminuted fracture of the femur trochanter (FTC5)	8	3.40	0	0.00	**0.02**
Depressed fracture of the parietal bone (P3)	0	0.00	5	3.03	**0.01**
Simple fracture of the maxilla (MA4)	15	6.38	35	21.21	**<0.001**
Fracture of the ascending ramus of the mandible (MD1)	4	1.70	21	12.73	**<0.001**
Fracture of the body of the mandible (MD3)	0	0.00	15	9.09	**<0.001**
Comminuted fracture of the mandible (MD4)	7	2.98	17	10.30	**0.004**
Mixed fractures of the mandible (MD5)	4	1.70	11	6.67	**0.01**

Simple fracture of the maxilla, ascending ramus, mixed and comminuted fractures of the mandible, comminuted fractures of the maxilla and fracture of the nasal bon occurred more frequently in blows than falls (Table 10).

Fractures of the body of the mandible and depressed fractures of the parietal bone occurred only in blow cases (Table 10).

The MMD was calculated from the presence/absence of the types of fractures. The MMD value (0.130) is greater than twice the standard deviation (0.004), indicating a significant difference between falls and blows.

A decision tree was built to identify the pattern and the fracture morphologies playing a key role in distinguishing between blows and falls. For this purpose, we interrogated the fracture morphologies that occurred twenty times or more, i.e. 16 types. The decision tree of our study integrated all 400 cases. The six variables identified by the decision tree were comminuted fractures of the coxal, fracture of the ascending ramus of the mandible, simple fracture of the maxilla, comminuted fractures of the mandible and the maxilla, fracture of the body of sphenoid. For each branch, the numbers of falls and blows are indicated (Figure 45).

More the half of fall cases (67.23%) show the same pattern of fracture morphologies: no comminuted fractures on the coxal, no fracture of the ascending ramus of the mandible, no simple fracture of the maxilla, no comminuted fractures on the mandible and the maxilla.

Fall cases can be differentiated too with the presence of comminuted fractures on the coxal (14%, n=33); or by the pattern composed of no comminuted fractures on the coxal, no fracture of the ascending ramus of the mandible, no simple fracture of the maxilla, no comminuted fractures of the mandible, presence of comminuted fractures on the maxilla, and presence of fracture of the sphenoid's body (2,55%, n=6).

Blow cases were characterized by the absence of comminuted fractures of coxal and the fracture of the ascending ramus of the mandible (12,73%, n=21). In 20% (n=33) of blow cases, the distinction can be made thanks to the absence of comminuted fractures of the coxal bone, no fracture of the ascending ramus of the mandible, and a simple fracture of the maxilla. In 9.70% (n=16) of blow cases, the distinction can be made thanks to the absence of comminuted fractures of the coxal bone, no fracture of the ascending ramus of the mandible, no simple fracture of the maxilla, and comminuted fractures of the mandible. In 16.36% (n=27) of blow cases, the distinction can be made thanks to the absence of comminuted fractures of the coxal bone, no fracture of the ascending ramus of the mandible, no simple fracture of the maxilla, no comminuted fractures of the mandible, presence of comminuted fractures of the maxilla and absence of fracture of the sphenoid's body.

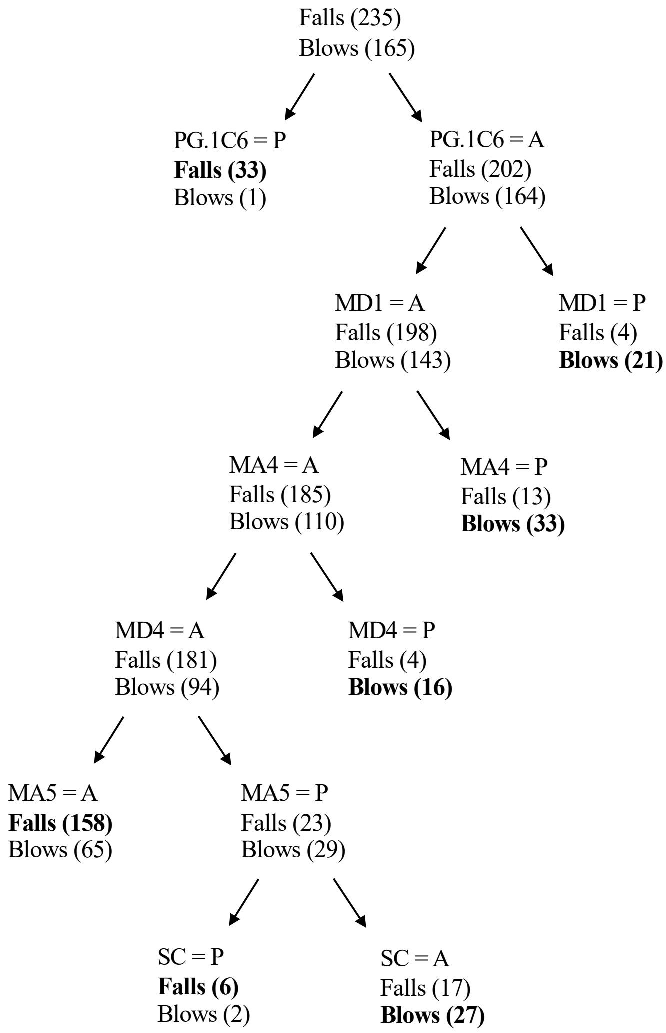

Figure 45: Decision Tree (A: no fracture, P: fracture)

Given that 38 cases of falls and 68 cases of blows were misclassified, the misclassification rate with the leave-one-out method was equal to 28%.

Therefore, the decision tree correctly classified 72% of the cases (83.83% of falls and 58.79% of blows). Perfect discrimination remains unrealistic, but the decision tree shows a strong discrimination potential between fall and blow cases using the presence of fractures on the coxal, mandible, maxilla, and sphenoid.

2.4. Discussion

2.4.1. Fracture morphology, sex, and age

The presence of morphology fractures by context, sex and age (Table 8-10) showed that linear fracture of the occipital, mixed fracture of the 7th lumbar vertebrae, and comminuted fracture of the coxal bone and sacrum are found significantly more often in females. This seems consistent with the fact that these bones are more likely to fracture during a fall (Table 10 and Table 16 in Annex III), and that nearly three times as many women in our sample were affected by falls (Figure 43). This prevalence of fractures concerning the lumbar vertebrae, the coxal and the sacrum can be explained by differences in bone structure between men and women, especially the effects of osteoporosis, pregnancy or lactation (Burke, 2012; Lapina & Tiškevičius, 2014; Levine, 2009; Sidon *et al.*, 2018; Timsit, 2005). We did not find literature about linear fracture of occipital.

About age, Table 8 shows that the frequency of comminuted fractures of the maxilla, fracture of the body, and mixed fracture of the mandible decreases significantly with age. This makes sense considering that mandibular and maxilla fractures are associated with blows (Table 10), and they decrease with age (Figure 37) (Ahmed *et al.*, 2018; Atilgan *et al.*, 2010; Beaumont *et al.*, 1985; Ghodke *et al.*, 2013; Kansakar *et al.*, 2017; Lee, 2009; Sojat *et al.*, 2001; Walker, 2001; Zaleckas *et al.*, 2013).

Linear occipital fracture was more frequent in individuals 30-39 years old, but we did not find literature about this fact (Table 8).

Table 8 shows mixed fracture of the 3rd, 4^{th,} and 6th ribs, fracture of the anterior arch of the 5th and 7th ribs, fracture of the posterior arch of the 9th, 10^{th,} and 11th ribs occurred more frequently, and fracture of the transverse process of the 12th thoracic vertebrae in individuals aged between 40 and 49 years are significantly more often fractured with increasing age, and these bone fractures are associated with falls (Table 10) which increase with age (Figure 44) (Agnew *et al.*, 2013; Talbot *et al.*, 2005).

2.4.2. Discussion

Fracture morphologies concerning the postcranial skeleton, the basicranium and the cranial vault occurred more frequently in falls. Those concerning the nasal bone, the maxilla or the mandible occurred more frequently in blow cases.

Falls

Regarding falls, males (80.85%, n=190) are more likely to fall than females (19.15%, n=45), and the number of falls increases with age. In fact, 43.83% (n=103) of the population are aged 40-49 (n=103) compared to 28.51% aged 20-29 (n=67).

On the 246 morphologies fracture, only 7 types are totally absent from fall cases: depressed fracture of the frontal (F3), middle arch fracture of the 12th rib (R12.2), diastatic fracture of the sphenoid (S2), compression of the 12th thoracic vertebrae (VT10.2), anterior arch fracture of

the 10th rib (R10.1), depressed fracture of the parietal (P3), and fracture of the body of the mandible (MD3) (Table 16 in Annex III).
These observations emphasized that fall-induced fractures were more frequent and well-distributed throughout the skeleton.

Blows

Blow is more common in males (92.12%, n=152) than in females (7.88%, n=13), and their number decreases with age. The number of blow cases decreases with age. Individuals aged 20-29 represent 46.67% (n = 77) of the blow cases, against 20% (n=33) for people aged 40 to 49. In 2001, Walker found that most of those involved in assaults were young men (Walker, 2001).
On the 246 morphologies fracture, 164 types are totally absent from blow cases (66.67%) (Table 16 in Annex III).
The types of fracture on the maxilla, mandible and nasal are significantly higher in blows (simple fracture of the maxilla, ascending ramus, mixed and comminuted fractures of the mandible, comminuted fractures of the maxilla). Moreover, fractures of the body of the mandible and depressed fractures of the parietal bone occurred only in blow cases.
These results are consistent with the literature because the head and face are the focal points of offenders' anger and these areas are psychologically linked to the victim's identity (Henn & Lignitz, 2004; Shepherd *et al.*, 1987; Strauch *et al.*, 2001; Wedel & Galloway, 1999).

Fractures of the skull

Our results showed that linear fracture on the frontal bone occurred more frequently in fall cases (7.23%, *n*=17) than in blows (1.21%, *n*=2).
According to Guyomarc'h and colleagues (2010), linear fracture occurred more frequently in fall cases than blows. This type of fracture is related to the height of the fall (Rowbotham *et al.*, 2018c). A linear fracture can occur by a direct blow at high velocity or indirect trauma as an extension of fractures originating at the impact site (Wedel & Galloway, 2014).

Comminuted fractures of the frontal bone are more frequent in fall cases (4.26%, *n*=10) than in blows (0%, *n*=0).
Our results show the opposite of Guyomarc'h and colleagues (2010) and Chattopadhyay and Tipathi (2020) results. Their study showed comminuted fractures were more predominant in blows than falls (Chattopadhyay & Tripathi, 2010; Guyomarc'h *et al.*, 2010). According to

Lefevre and colleagues (2015), comminuted fractures occur in falls and blows in similar proportions (Lefèvre *et al.*, 2015).

Depressed fractures of the parietal bone are only present in blow cases (3.03%, n=5). Our results are concordant with the literature (Galloway & Wedel, 2014c; Guyomarc'h *et al.*, 2010; Kranioti, 2015; Lefèvre *et al.*, 2015).

Ring fractures of the basicranium are totally absent from our sample. We expected to observe it because according to the literature, ring fractures may be produced by fall from height, collisions with automobiles or a blunt violence of the mandible or back of the head/neck (Galloway & Wedel, 2014c; Kranioti, 2015; Ta'ala *et al.*, 2006; Zhang *et al.*, 2022). However, the study of Rowbotham (2018) only registered 5 ring fractures on 298 individuals.

In a general way, our results are inconsistent with many studies showing that fractures of the cranial vault and above the HBL cannot be caused by falls, except in the case of multiple falls, falls from height or hits an edge or an angle; therefore they will be less frequent than in the case of blows (Ehrlich & Maxeiner, 2002; Fracasso *et al.*, 2011; Geserick *et al.*, 2014; Guyomarc'h *et al.*, 2010; Kremer *et al.*, 2008; Kremer & Sauvageau, 2009; Maxeiner & Ehrlich, 2000; Walcher, 1931).

Our results showed that a fracture of the body of the sphenoid bone is more frequent in cases of fall (8.94%, n=21) than in blows (3.64%, n=6).
No literature has been found on this subject, except in a global way. Fractures of the basicranium occurred in fall cases but could indirectly result from blows (Rogers, 1992).

Our results showed that simple maxilla fractures occurred more frequently in blows (21.21%, n=35) than in falls (6.38%, n=15).
It is the same for multiple maxilla fractures, 21.21% (n=35) in blows and 12.77% (n=30) in falls, and fracture of the nasal bone (19.39%, n=32 for blows and 15.32%, n=36 for falls).
These results concord with many authors who said and showed that one of the most common injuries is a facial injury (Beaumont *et al.*, 1985; Brook & Wood, 1983; Erdmann *et al.*, 2008; Guyomarc'h *et al.*, 2010; Henriques *et al.*, 2023; Henriques *et al.*, 2023; Hussain *et al.*, 1994; Kahramansoy *et al.*, 2011; Redfern, 2017; Ribeiro *et al.*, 2004; Scherer *et al.*, 1989; Starkhammar & Olofsson, 1982; Walker, 2001; Wedel & Galloway, 2014).
The total absence of Le Fort fractures may seem surprising because they occurred often in interpersonal violence (Galloway & Wedel, 2014c; Kranioti, 2015). During the scoring of our study, some fractures could have been considered as Le Fort fractures, and there was a discussion with the radiologists, but we finally came to the decision that fractures had to strictly

and completely correspond to Le Fort's definition to enter this category, yet those we could observe only partially adhered to the definition as they were incomplete.

People aged 20-29 are more affected by mandible fractures because they are more implicated in blow cases.

Fractures on the ascending ramus (angle, condylar) of the mandible occur in 12.73% of bows (n=21) and 1.70% (n=4) of falls.

Comminuted fractures of the mandible were more frequent in bows than falls (2.98%, n=7).

Mixed mandible fractures occurred in 6.67% of blows (n=11) and 1.7% of falls (n=4).

Fractures of the mandible occurred frequently in physical assaults (Beaumont *et al.*, 1985; Ellis *et al.*, 1985; Lee, 2009; Paza *et al.*, 2008; Silvennoinen *et al.*, 1992; Sojat *et al.*, 2001; Wedel & Galloway, 2014; Zaleckas *et al.*, 2013)

Fracture of the body of the mandible occurred in 9.09% of blow cases and was totally absent in the fall sample. According to Rogers, this type of fracture occurred frequently in interpersonal violence due to the prominent position of the chin (Rogers, 1992).

People between the ages of 20 and 29 are more affected by a mandibular fracture because they are likely to be involved in interpersonal violence.

Fracture of the upper extremity

Comminuted scapula fractures only occur in fall cases (5.96%, n=14).

No literature was found about the etiology of comminuted fracture of the scapula but fractures of this bone are uncommon and result from falls or motor vehicle incidents (Burke, 2012; Court-Brown, 2015; Henriques *et al.*, 2023; Wedel & Galloway, 2014).

Fractures of the thoracic cavity

In our study, different types of rib fractures are more frequent in fall cases than in blow cases (where, for some, they are completely absent). Rib fractures are more widespread in fall cases. In blows, fractures affect more the last ribs and their posterior arch.

People aged 40 and 49 years are more implied by these types of fractures, which could be explained because this age group are more frequent in falls.

Rib fractures are complex and are an essential indicator of trauma severity (morbidity and mortality increase with increasing numbers of ribs fractured) (Kani *et al.*, 2019; Restrepo *et al.*, 2009; Senekjian & Nirula, 2017; Talbot *et al.*, 2017). They are commonly associated with high falls (Rowbotham *et al.*, 2018a).

Oblique/backward angulation fracture of the body of the sternum only occurred in fall cases (2.98%, n=7). Sternal fractures can result from motor vehicle accidents, contact sports, falls, and assaults (Kani *et al.*, 2019; Khoriati *et al.*, 2013; Restrepo *et al.*, 2009). Oblique sternum fractures often occur in car accidents because of the sea belt (Schulz-Drost *et al.*, 2018). According to Henriques *et al.* (2023), sternal fractures were more frequent in falls.

Fractures of the vertebrae

Lumbar and thoracic vertebrae compressions are absent in blow cases. It is the same with the fracture of the transversal process.

These results concord with Henriques *et al.* (2023).

The most common etiology of vertebral compression fractures is osteoporosis, but it can occur after high energy mechanisms (such as fall from height) (Donnally III *et al.*, 2023).

Falls frequently cause transverse process fracture (Rowbotham *et al.*, 2018a; Wedel & Galloway, 2014).

Mixed fractures of the 1st lumbar vertebrae occurred more frequently in females (8.62%, n=5) than males (1.46%, n=5) and in people aged 40-49 (5.15%, n=7). This prevalence can be explained by pregnancy and lactation (Kovacs, 2011; Sidon *et al.*, 2018).

Fractures of the pelvic girdle

Comminuted fracture, mixed fracture of the sacrum, and coccyx fracture are only present in falls. Juxta-articular/articular fractures of the sacrum are more frequent in falls (5.11%, n=12) than blows (0.61%, n=1).

Comminution of the sacrum results from high falls (Rowbotham *et al.*, 2018a).

Comminuted sacrum fractures are more frequent in females (13.79%, n=8) than in males (5.26%, n=18). The research of Rowbotham *et al.* (2018a) showed that this type of fracture was less likely to occur in males.

Our results concord with one of our previous studies, the bone can be weakened by pregnancy, lactation, and postmenopausal females (Burke, 2012; Henriques *et al.*, 2023; Lapina & Tiškevičius, 2014; Levine, 2009; Timsit, 2005).

Comminuted fractures of the coxal bone are more frequent in falls (14.04%, n=33) than blows (0.61%, n=1). Mixed fractures of the coxal only occurred in falls (3.83%, n=9).

Falls generated multiple fractures of the coxal (Henriques *et al.*, 2023).

Comminuted fractures of the coxal bone are more frequent in females (18.97%, n=11) than in males (6.73%, n=23). A hip fracture can occur because of pregnancy-associated transient osteoporosis (Hadji *et al.*, 2017).

Fractures of the lower extremity

Comminuted trochanteric fractures of the femur only occur in fall cases (3.40%, n=8). This is concordant with the literature (Guo *et al.*, 2020).

Skeletal fracture patterning

The decision tree proposed in our study showed the importance of fractures located on the coxal, on the mandible, on the maxilla and the sphenoid because it allows a distinction between blows and falls. The fracture morphologies allowing a such differentiation are comminuted fractures of the coxal, fracture of the ascending ramus of the mandible, simple fracture of the maxilla, comminuted fractures of the mandible and the maxilla, fracture of the body of sphenoid. By using this tree on our study sample to predict the etiology of fractures and using a “leave one out” (LOO) procedure, the decision tree correctly classified 72% of the cases.

The Hat Brim Line (HBL) is defined as the area above the Frankfort horizontal plane, located between the line passing through the glabella (G-line) and the line passing through the center of the external auditory meatus (EAM-line) (Kremer *et al.*, 2008). This area was often used in the distinction of falls and blows. The rule was created by Walcher in 1931 and said that injuries from falls do not lie above the HBL when some conditions are fulfilled (Geserick *et al.*, 2014; Walcher, 1931).

The study of Kremer *et al.* (2008) show that blow injuries are often found above HBL.In Kremer *et al.* (2009), injuries inflicted by blows are often situated above HBL, and a skull fracture inside HBL is found equitably in both etiologies (falls and blows).The results of Guyomarc’h *et al.* (2010) show a strong discrimination potential between fall and blow cases with four criteria, including fractures above the HBL (in favor of blows).

These studies show that the HBL rule must be used carefully, and perfect discrimination remains unrealistic.

Our results confirm the limitation of the use of the HBL rule. The criteria highlighted by our decision tree are all below the HBL, and a fracture morphology above the HBL cannot distinguish blows. This distinction can be made by the only presence of fractures on the mandible (ascending ramus or comminuted) or maxilla (simple fracture), or by the combination of comminuted fractures of the maxilla and the absence of fracture of the sphenoid’s body. Falls can be determined by the presence of comminuted fracture of the coxal bone, or by the totally absence of fractures on the coxal, mandible, and maxilla, or by the combination of comminuted fractures of the maxilla and the presence of fracture of the sphenoid's body.

It should be noted that some fractures are important criteria in the distinction between falls and blows:

- Fractures of the face for blows, since this location is the main rage focus of the perpetrator because this area is psychologically linked to the victim's identity (Henn & Lignitz, 2004; Shepherd *et al.*, 1987; Strauch *et al.*, 2001; Wedel & Galloway, 1999).
- Fractures of the coxal bone, since multiple fractures of the hip bone are significantly more frequent in falls than blows (Henriques *et al.*, 2023).
- Fractures of the basicranium, since according to Kratter, blows can cause injury in every region except for the base of the skull (Fracasso *et al.*, 2011; Kratter, 1921)

Limitations

Intraobserver and interobserver errors were not tested for all types of fractures since only 30% of cases were selected aleatory (all types were not totally present).

Intraobserver error showed 100% agreement for the criteria used to build the decision tree, except for the simple fracture of the maxilla (65%).

Interobserver error (anthropologist) showed 100% agreement for the fracture of the sphenoid's body, comminuted fractures of the coxal and fracture of the ascending ramus of the mandible. Comminuted fractures of the maxilla showed 78% agreement, and simple fracture of the maxilar and comminuted fractures of the mandible 65%.

3. Elaboration of a new method in the distinction between blows and falls by random forest classification

The obtained data was used on the published original paper:

Mélanie Henriques, Vincent Bonhomme, Eugénia Cunha, Pascal Adalian. **Blows or falls? Distinction by random forest classification**. ***Biology***. 2023; 12(2):206. https://doi.org/10.3390/biology12020206

3.1. Introduction

For several years, a lot of research has been conducted to try to distinguish between falls and blows. The most cited work is the Hat Brim Line (HBL) rule which has often been simplified as fractures resulting from falls are located within the HBL, whilst fractures resulting from blows may be found above and within the HBL yet not on the base of skull. Recent studies have found that the HBL rule has to be used very carefully because their results do not match the definition (Geserick *et al.*, 2014; Henriques *et al.*, 2023; Kremer *et al.*, 2008; Kremer & Sauvageau, 2009; Lefèvre *et al.*, 2015).

We previously showed that the discrimination between falls and blows can be discussed by the site and the number fractures found on the skull and the trunk (Henriques *et al.*, 2023).

The purpose of this research is primarily to find additional useful criteria (i.e. the type of fractures) in the distinction of both etiologies. Furthermore, we aim to test with random forests various models by selecting and combining criteria with the highest predictability rates.

3.2. Material and methods

3.2.1. Dataset description

Following the standards of the National Consultative Ethics Committee for health and life sciences (CCNE), National Council of Ethics for the Life Sciences (CNECV), and the Helsinki Declaration of 1975 concerning the privacy and confidentiality of personal data, our dataset consisted in 400 anonymized patients presenting fractures from falls or blows and between 20 and 49 years old. The CT scans of our sample were collected from the PACS (Picture Archiving and Communication System) in the Assistance Publique-Hôpitaux de Marseille (AP-HM, France), the Centro Hospitalar e Universitário de Coimbra and the Centre Hospitalier Regional et Universitaire de Nancy. The scanner slices were 0.6 mm and 1.25 mm thick according to the acquisition protocol. Each individual was reviewed in the three anatomical planes (axial, coronal, and sagittal) using the window viewing presets for bone and adjusted manually on AW Workstation (AW server 2.0, GE HealthCare, Milwaukee, USA) and Horos® (version 3.3.5, © 2021 Horos Project). Three-dimensional volume renderings were also used to identify the fractures.

The following variables were available: the sex and age (later referred as 'baseline') in one hand, the 372 types of fractures for all 57 bones in the other. We used 2 classifications AO/OTA and Galloway and Wedel (2014) when it was possible, otherwise we observed the presence/absence of the fracture on different parts of a bone (Marsh *et al.*, 2007; Wedel & Galloway, 2014). The observations were done using multiplanar reconstructions (MPR), maximum intensity projection (MIP) and volume rendering (VR) reconstructions on Horos version 3.3.5®.

To cope with absent and very rare events (less than 5%), like fractured bones with low frequencies, we excluded 534 types and 29 bones. The final dataset included 15 types of fractures and 28 bones.

On the 28 remaining bones, 12 anatomical regions were defined: cranium, basicranium, cranial vault, face, mandible, scapula, ribs, thoracic vertebrae, lumbar vertebrae, sacrum, coxal bone and femur.

3.2.2. Inter- and intra-observer errors

To assess the repeatability, we randomly selected 30 individuals of the sample. Inter and intra-observer variations were evaluated using Cohen's kappa coefficient with {KappaGUI} R package.

3.2.3. Random forest approach

Our aim was to predict the circumstances of observed fractures, that is, blow or a fall, using the available etiology. We chose to use random forest approach since it an appropriate supervised learning technique when the amount of observations is lower or of same magnitude as the number of variables (Breiman, 2001; Genuer & Poggi, 2019). It is also adapted to classification problems that include qualitative and quantitative variables.

3.2.4. Statistical environment

All analyses were done in the R 4.1.3 statistical environment ('R', n.d.), using the following packages: *randomForest* to model and predict using random forests (Liaw & Wiener, 2002), *pROC* to calculate ROC curves (Robin *et al.*, 2011), *tidyverse* for general data manipulation, programming, and data visualization (Wickham *et al.*, 2019).

3.2.5. Model Selection

As implemented in *randomForest* (Liaw & Wiener, 2002) , the random forest algorithm comes with three internal parameters: `mtry` (the number of variables randomly sampled as candidates at each split), `nodesize` (the minimum size of terminal nodes) and `ntree` (the number of trees to calculate). Additionally, our dataset also allows different approaches: which `data` to use (bones, typology, anatomical region and whether to include or not the sex/age of the patient) and the `metric` of the data (quantitative, ternary, or semi-qualitative {0, 1, 2+} or binary {0/1}).

Altogether these 5 parameterizing dimensions allows many different models to be trained and the successive steps described below aimed at reducing this number to a few, accurate models.

3.2.6. Grid search for hyper parameters optimization

We first explored the sensibility of random forest parameters and their effects on model accuracies. We used a grid search approach on the five dimensions. The `mtry` parameter was the only one that vary between datasets. A default and sensible value for these parameters is the square root of the number of variables used, rounded to the lower integer. We circumvented this by defining `mtry_k` which simply is a multiplicative factor to this default value. For a, say 36 variables dataset, mtry_k=1 leads to a mtry=6, mtry_k=0.5 to a mtry=3, and mtry_k=2 to a mtry=12, etc.

The full combination of model tested was : ```mtry_k``` {0.25, 0.5, 1, 2, 4}; ```nodesize``` {1, 2, 5, 10}; ```ntree``` {101, 501, 1001, 2001}; `metric` {quantitative, ternary, binary}; ```datasets``` {baseline alone, bone, bone+baseline, type, type+baseline, anatomical region, anatomical region + baseline}. This resulted in 1680 models.

The dataset was randomly partitioned in 300 patients for the training set, and 100 patients for the testing set, the latter being never "seen" by the model while training. To have an estimate of parameters elasticity and the impact of such partitioning, we actually repeated the entire grid search process for 10 different sets of partition, following the same scheme.

3.2.7. Benchmarking models with fixed internal parameters

After fixing random forest internal parameters, we ran the same models and explored the structure of their predictions, included the contrast between the error obtained on the train versus on the test partition.

Model selection was also made here to select both the `dataset` and `metric` to use. Accuracy, i.e. low error, was the first criterium. We also considered how the models generalized: ideally, we would expect similar errors which would indicate that the model is not overfitting training data. Finally, parsimony helped us select between `metric`: for comparable model performance, the simpler (e.g. binary versus ternary) the better.

3.2.8. *Class-wise predictions for the final models*

Finally, on the four final models, we explored their results as regards their prediction in terms of etiology alone, etiology for each sex and etiology for age classes. To ease graphical interpretation, we binned the continuous age variables into 10-years bins, ranging from 20 to 49.

3.2.9. *Variable importance and their sign*

Variable importance, i.e. how each bone/anatomical results weights on the classification task was calculated. We also attempted at "signing" these contributions towards either blow/fall. This cannot be retrieved directly with random forests but the marginal distributions of occurrence for each of the bone/region allow approach them. The proportion of broken bones/region were calculated and adjusted for the overall sample size of each etiology, otherwise unbalanced.

3.2.10. *Predicting new patients*

Regarding new individuals, there is no guaranty of full information. Some fractures may not be recorded, some bones may just be missing and difficult to assess whether they were broken or not when the person passed away. In forensic contexts, there are many cases where the information about the context is unknown and where it is paramount to establish whether the manner of death, that is, whether it was accidental, homicide or suicide.

3.3. Results

3.3.1. *Inter- and intra-observer errors*

The inter- and intra-observer errors were evaluated using Cohen's kappa (Table 11) (Cohen, 1968; Cohen, 1960). A table taken from Landis and Koch (1977) was used for agreeing to evaluation (Table 12) .

Table 11: Inter- and intra-observer errors of the assessment of the presence and the number of fractures on fourteen anatomical regions using Cohen's kappa ("-":the kappa was not provided because the calculation made no sense)

Localization	Absence/Presence	Absence/Simple/Multiple	Quantitative

	Inter-observer	Intra-observer	Inter-observer	Intra-observer	Inter-observer	Intra-observer
Basicranium	0.71	1	0.72	1	0.60	0.78
Cranial Vault	0.84	1	0.84	1	0.84	1
Face	0.9	0.9	0.91	0.82	0.82	0.82
Mandible	0.87	1	0.75	1	0.75	1
Scapula	0.84	1	0.84	1	0.84	1
Ribs	0.72	1	0.68	0.93	0.41	0.57
Thoracic V.	0.76	0.84	0.77	0.68	0.78	0.54
Lumbar V.	0.92	1	0.92	0.93	0.71	0.75
Sacrum	1	1	0.86	1	0.59	0.86
Coxal	1	0.87	1	0.87	1	1
Femur	1	1	1	1	1	1
Frontal	0.78	1	0.79	1	0.79	1
Parietal	1	1	1	1	1	1
Occipital	1	1	1	1	1	1
Temporal	0.84	1	0.84	1	0.69	1
Sphenoid	0.84	1	0.84	0.72	0.84	0.72
Ethmoid	1	1	1	1	1	1
Nasal	1	1	1	1	1	1
Maxilla	0.71	0.84	0.72	0.84	0.72	0.84
Zygomatic	1	1	0.86	0.86	0.86	0.86
Mandible	0.87	1	0.75	1	0.75	1
Scapula	0.84	1	0.84	1	0.84	1
Rib3	0.61	1	0.5	1	0.50	1
Rib4	0.76	1	0.77	1	0.77	1
Rib5	1	1	1	1	0.86	1
Rib6	0.84	0.87	0.84	0.88	0.69	0.88
Rib7	0.67	0.81	0.68	0.83	0.68	0.83
Rib8	0.44	0.91	0.48	0.84	0.48	0.84
Rib9	0.90	0.90	0.82	0.91	0.73	0.82
Rib10	0.76	0.89	0.54	0.89	0.54	0.89
VTH12	0.64	1	0.64	1	0.64	1
VLO1	1	1	0.90	0.90	0.81	0.81
VLO2	1	1	1	0.90	1	0.90
VLO3	0.71	1	0.71	1	0.71	1
VLO4	0.84	0.87	0.84	0.87	0.84	0.87
VLO5	0.71	0.76	0.71	0.76	0.71	0.76
Coxal	1	0.87	1	0.87	1	0.87
Sacrum	0.84	1	0.84	1	0.84	1
Femur	1	1	1	1	1	1
Simple Fracture Zygomatic Process of Temporal	0.78	1	0.78	1	1	0.78

Petrous Portion of Temporal	0	1	0	1	0	1
Linear Fracture of Sphenoid	1	0.78	1	0.78	1	1
Body of Sphenoid	1	1	1	1	1	1
Ethmoid	1	1	1	1	1	1
Nasal	1	1	1	1	1	1
Simple Fracture Maxilla	0.65	0.65	0.65	0.65	0.65	0.65
Comminuted Fracture Maxilla	0.78	1	0.78	1	0.78	1
Ascending Ramus of Mandible	1	1	1	1	1	1
Comminuted Fracture of Mandible	0.65	1	0.65	1	0.65	1
Transverse Process of VL1	1	1	1	1	1	1
Transverse Process of VL2	1	1	1	1	1	1
Transverse Process of VL3	0.63	1	0.63	1	0.63	1
Transverse Process of VL4	0.78	0.84	0.78	0.84	0.78	0.84
Comminuted Fracture of Coxal Bone	1	1	1	1	1	1

Table 12: Agreement by Landis, Koch (1977)

Kappa (K)	Strengh of agreement
<0	Poor
0.00 - 0.20	Sight
0.21 - 0.40	Fair
0.41 - 0.60	Moderate
0.61 - 0.80	Substantial
0.81 - 1.00	Perfect

The results show a perfect and substantial agreement for most variables with a binary quotation. Only the 8th rib shows an error inter-observer moderate with 0.44. Only fractures on the petrous portion of temporal bone have a sight inter-observer error (0).

The results show a perfect and substantial agreement for most variables with a ternary quotation. Only the 3, 8 and 10th ribs show an error inter-observer moderate with 0.5, 0.48 and 0.54. Only fracture on the petrous portion of temporal bone has a sight error inter-observer (0).

The results show a perfect and substantial agreement for most variables with a quantitative quotation. Other variables show an error inter-observer moderate between 0.48 and 0.60 for fractures in the basicranium, ribs (3, 8 and 10th) and sacrum. Other variables show an error intra-observer moderate between 0.54 and 0.57 for fractures ribs and thoracic vertebrae.

The best reproducibility are in all types of quotation of the type of fractures, ternary quotation of fractures on anatomical regions and more generally, the binary quotation.

3.3.2. Parameter optimization

As shown in Figure 46, we run each model several times for different values of mtry_k, nodesize and ntree parameters. For each run, we measured the error rate (i.e. 1-accuracy) of the model.

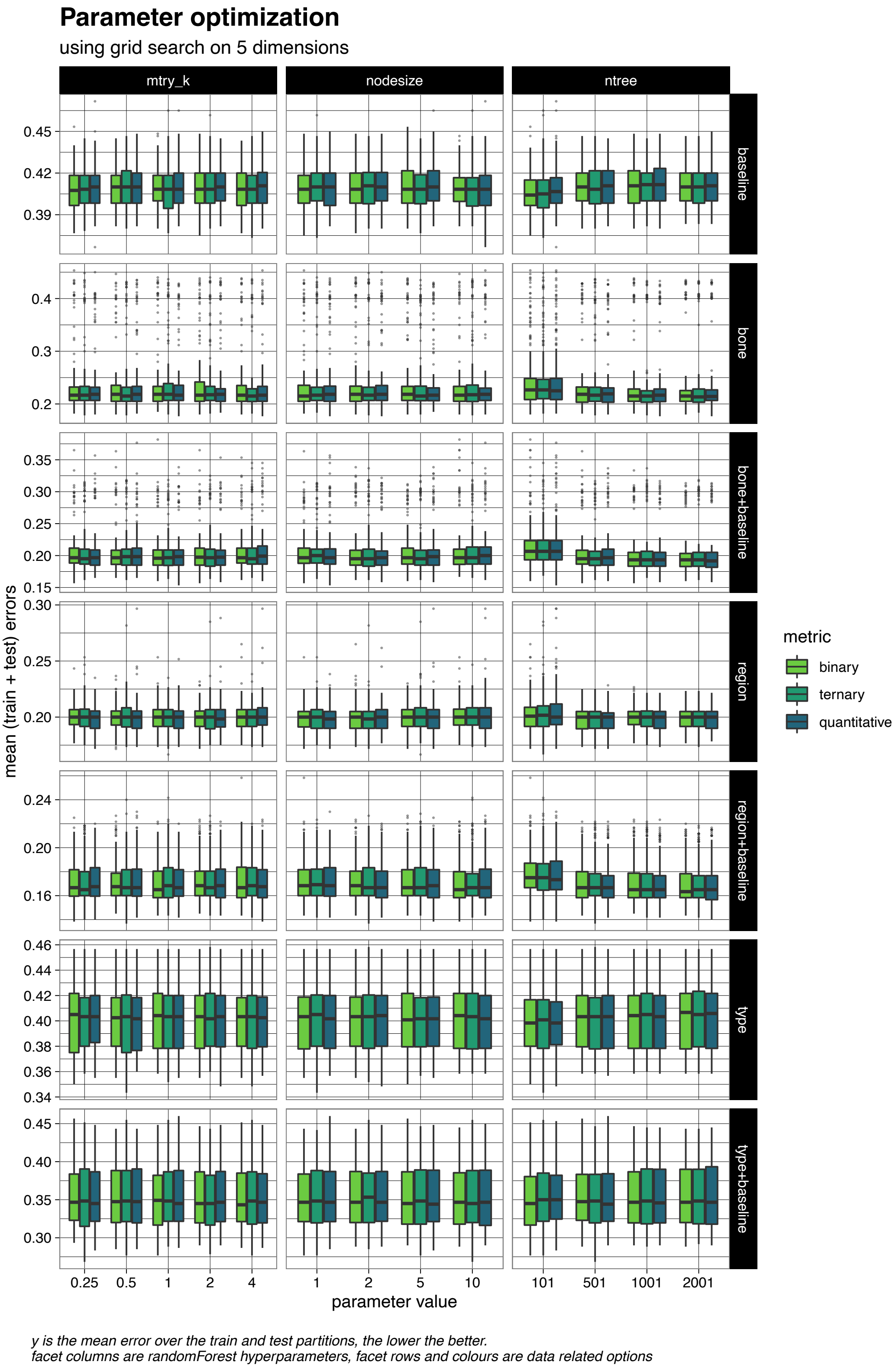

Figure 46: Random forest parameters optimization of all the models

For each box Figure, the green box represents that the central 50% data lie in this section; the bold bar is the median value; the upper and lower black bars are the greatest and least values, excluding outliers; and finally, the black pluses represent the outliers.

As can be seen from the box Figure, all rating models have similar thresholds for the error rate despite the variation of the mtry_k, nodesize and ntree parameters.
However, note that the mtry_k=1, nodesise=5, ntree=501 parameters show a lower error rate as the models based on the observation of fractures on the bone with or without baseline and on anatomical regions.

3.3.3. Benchmarking models

Various models were tested using the parameters selected above (Figure 47).

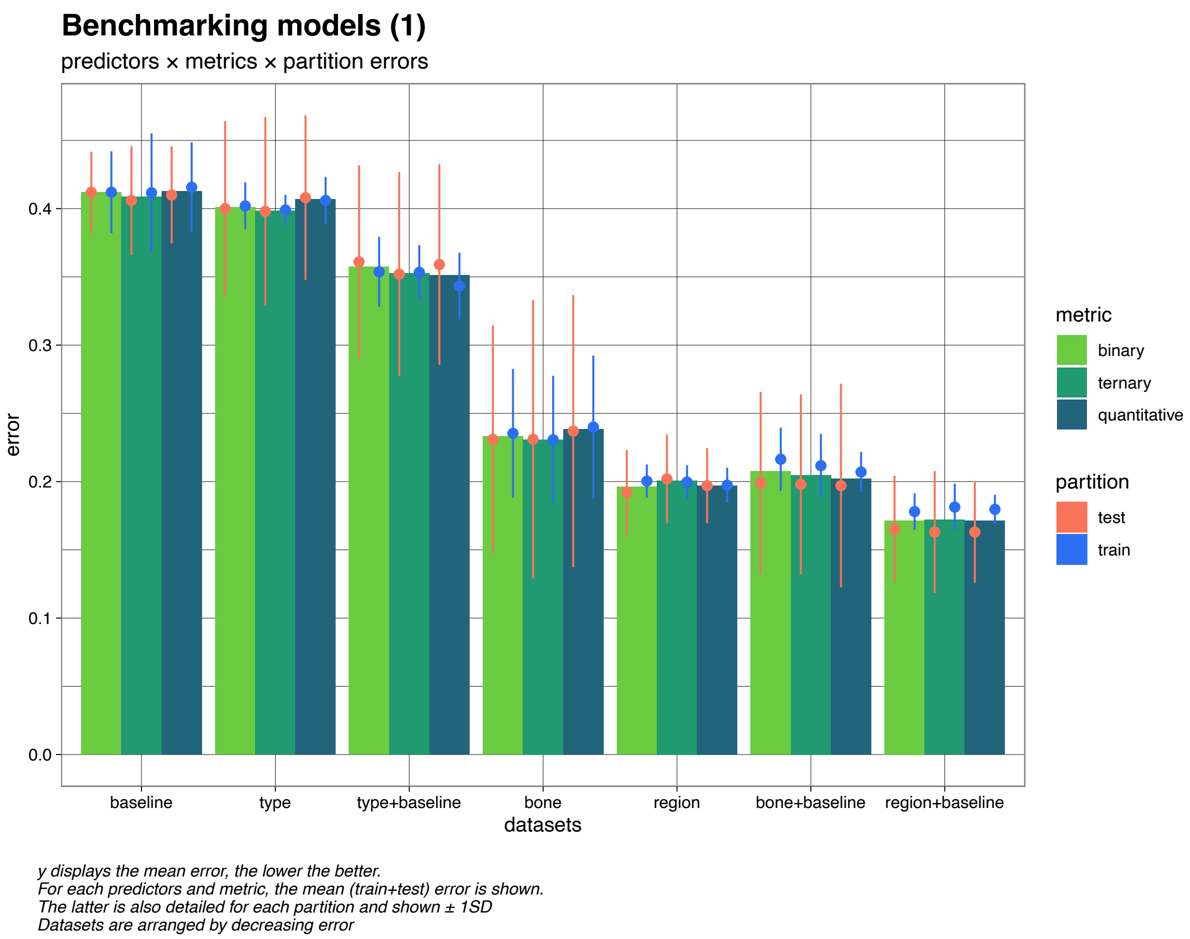

Figure 47: Error rates of all the models in test and train samples by random forest

The error of the models based on the type of fractures or only with baseline is 35% and more. We can see that the best models are inferior to 25% et are the ones which are based on the bone or the region of fractures, with or without the baseline. So, for the next step, we leave aside the type of fractures.

The results are similar for the three rating systems (binary, ternary and quantitative). We decided to keep the binary quotation because it’s shown very few inter- and intra-observer.

3.3.4. *Exploring class-wise predictions for the final 4 models*

The results of the final 4 models: bone, bone and baseline, region of fracture, and region of fracture and baseline are presented on Figure 48.

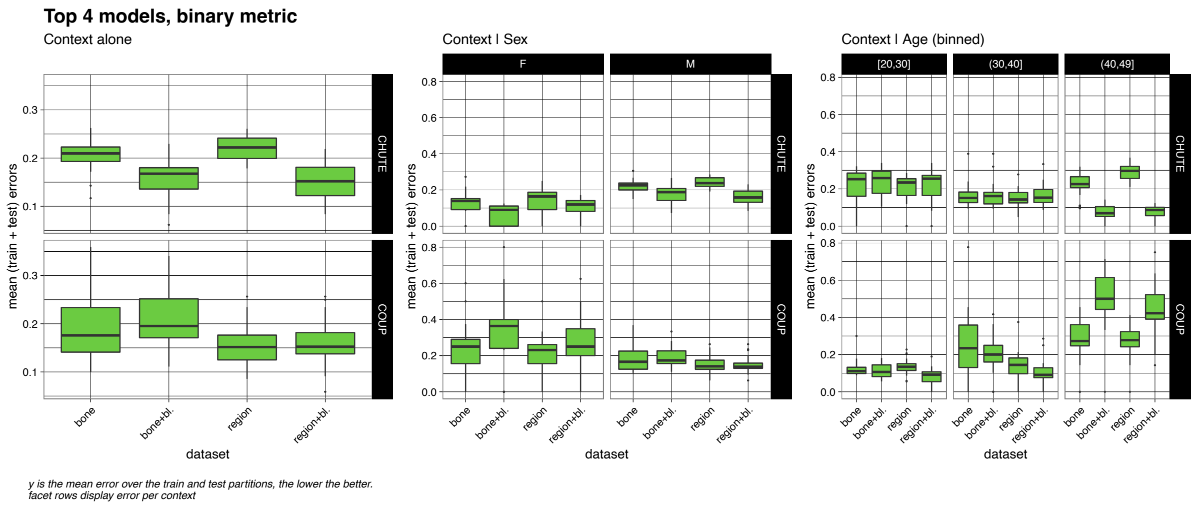

Figure 48: Error rate of the models based on fractures on the anatomical regions and bone with or without baseline by etiology, sex, and age

The mean error for fall is between 12% and 24%. The best model is those based on regions of fractures and baseline.

The mean error for blow is between 12% and 25%. The best model is those based on regions of fractures with or without baseline.

The second part of the figure shows the relationship between context and sex. The rate error in falls for females varies between 0 and 20%, for males it's between 14 and 28%. For blows, the rate error varies for females between 17 and 40%; and for males between 12 and 23%.

The third part of the figure shows the relationship between context and age. The rate error in falls for individuals aged between 20 and 29 years is 17 to 30%; for individuals aged between 30 and 39 years is 12 to 20%; and for individuals between 40 and 49 years is 10 to 32%. The rate error in blows for individuals aged between 20 and 29 years is 7 to 15%; for individuals aged between 30 and 39 years is 9 to 37%; and for individuals between 40 and 49 years is 25 to 61%.

3.3.5. *Variable importance in model*

The variable importance of the final 4 models: bone, bone and baseline, region of fracture, and region of fracture and baseline are presented on Figure 49.

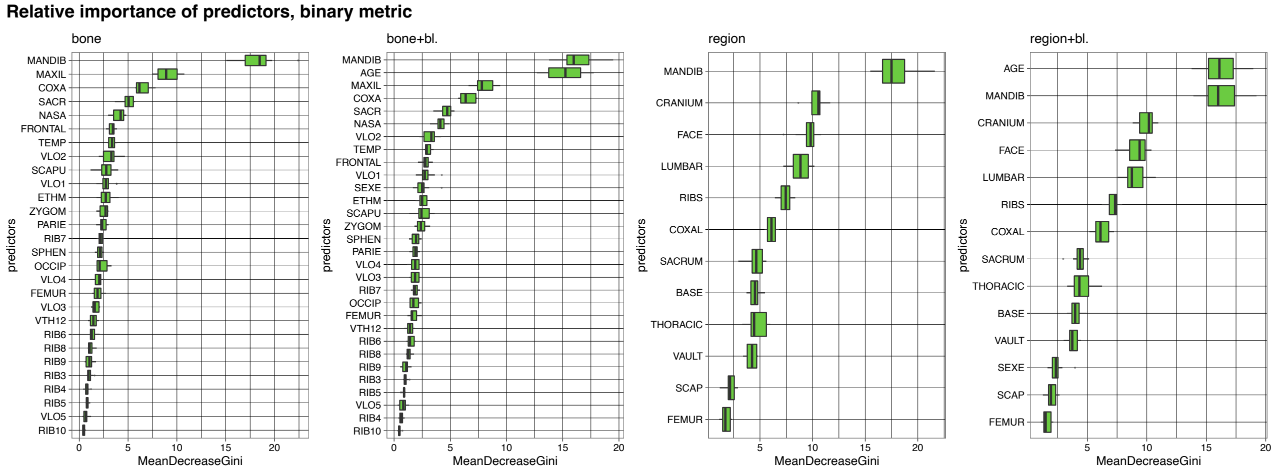

Figure 49:Variable importance for the 4 final models based on fracture on the anatomical regions and bones with or without baseline

The predictors most important in the model based on bone are fractures on mandible, on the maxilla bone, coxal bone, sacrum, and nasal bone.

The predictors most important in the model based on bone and baseline are fractures on mandible, the age of the individual, fractures on the maxilla bone, coxal bone and sacrum.

The predictors most important in the model based on the anatomical region are fractures on mandible, cranium, face, lumbar and ribs.

The predictors most important in the model based on the anatomical region and baseline are the age of individual, fractures on mandible, cranium, face, and lumbar.

We can see that fractures on the cranium, mandible on the pelvic girdle, lumbar and ribs are very important in the distinction between falls and blows.

Note that the two most important parameters in these four models are the mandible and the age of the patient.

In order to observe which localization of fracture tend to be more caused by blows or falls, we made the Figure 50.

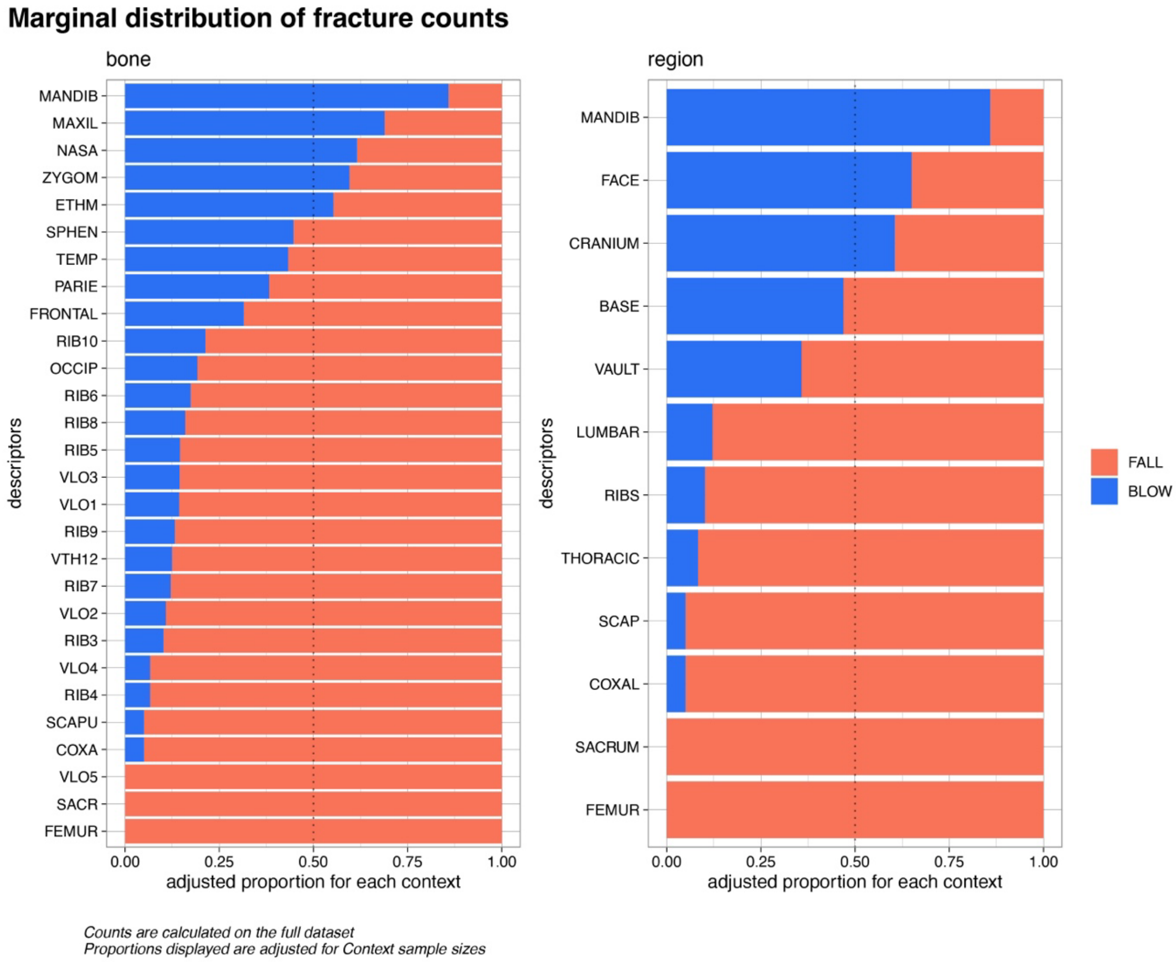

Figure 50: Distribution of the fractures on the anatomical region and bones according to the etiology

This figure shows the distribution of the best relevant parameters in the distinction between falls and blows.

On the left, it's the fractures on bones. Fractures on the mandible, maxilla, nasal, zygomatic, and ethmoid bones tend to be more frequently due to blows than falls. No fractures of the 5th lumbar vertebrae, sacrum and femur have been observed in blow cases. The other fractures are more presents in fall cases than in blow cases.

On the right side of the Figure 50, we can observe the classification of fractures present in the anatomical regions. Fractures on the mandible, face and cranium are more observed on blows than falls. No fractures on the sacrum and femur were observed on blow cases. Fractures on the basicranium, vault, lumbar vertebrae, ribs, thoracic vertebrae, scapula and coxal bone are more frequent in fall cases than in blows.

3.4. Discussion

3.4.1. Repeatability

The results presented a substantial to perfect agreement for most of the variables especially in case of binary quotation.

3.4.2. Fracture location, sex, and age

The Figure 48 showed differences between the rate of error between males and females and between the class of age could in blow cases. The error rate is important for females and individuals aged between 40 and 49 years.

These differences could be explained by the fact that the context of fracture on the medical reports may be misinformed or because of the bone's quality. Bone can be weakened by pregnancy, lactation or postmenopausal females among other things (Burke, 2012; Lapina & Tiškevičius, 2014; Levine, 2009; Timsit, 2005). This fragility would be more conducive to fractures.

3.4.3. Model of prediction

Random forests allowed us to construct models optimized on the observed data, discovering new classification criteria. The best prediction models are based on a binary quotation of fractures on 12 anatomical regions or 28 bones with or without baseline (age and sex). These models allow a prediction between 77 and 83%.

Fractures on the basicranium, vault, lumbar vertebrae, ribs, thoracic vertebrae, scapula and coxal bone are more frequent in fall cases than in blows. These results are in agreement with Henriques *et al.* (Henriques *et al.*, 2023).

We will discuss fractures on the basicranium and on the cranial vault further because this is a particular subject in the distinction between blows and falls.

According to the literature, thoracolumbar injuries can result from motor vehicle accidents, fall from a significant height and a direct blow (Burke, 2012; Cooper *et al.*, 1995, 1993; Hsu *et al.*, 2003; Meldon & Moettus, 1995; Miller *et al.*, 2000; Richter *et al.*, 1996; Samuels & Kerstein, 1993).

Rib fractures are common injuries and can result from sport, direct blow or kicking, falls, high-velocity trauma and cardiopulmonary resuscitation (Abel & Ramsey, 2013; Atanasijevic *et al.*, 2009; Barrett-Connor *et al.*, 2010; Casali *et al.*, 2014; Kim *et al.*, 2013; Petaros *et al.*, 2013; Saukko & Knight, 2016; Talbot *et al.*, 2017).

Pelvic fractures are common in motor vehicle accidents, falls, and sport-related accidents (Balogh *et al.*, 2007; Burke, 2012; Court-Brown, 2015; Wedel & Galloway, 2014).
According to the literature, scapula fractures can result from falls, motor vehicle incidents or direct blow (Burke, 2012; Court-Brown, 2015; Ramponi & White, 2015; Rowbotham *et al.*, 2018a; Wedel & Galloway, 2014).

Fractures on the mandible, maxilla, nasal, zygomatic, and ethmoid bones tend to be more frequently due to blows than falls. Most of these results are concordant with Henriques *et al.* (2023).
This is relevant with the study of Wulkan *et al.* (2005), interpersonal violence caused panfacial fractures and as for isolated bone structures, the mandible and the nasal had the highest incidence of fractures. Panfacial fractures involved fractures of frontal bone, maxilla, zygomatic complex, nasoethmoid-orbital region, sphenoid and mandible (Ali & Lettieri, 2017). In our case, fractures on frontal bone and on sphenoid bone are more frequent in falls than blows.
According to Laski *et al.* (2004) the most frequent etiology of facial trauma was assault (75%), mandible fracture occurred in 46.7% of cases.
The head and the neck are regions the most affected by violence (Downing *et al.,* 2003).

When we approach the subject of the distinction between blows and falls based on skull fractures, it is difficult not to think of the Hat Brim Line (HBL) rule created by Walcher in 1931. This last one is an area of the skull between two lines that run parallel to the Frankfurt horizontal plane; the superior line passes through the glabella and the inferior line runs through the external auditory meatus (Kremer *et al.*, 2008).
This rule has often been simplified as fractures resulting from falls are located within the HBL, whilst fractures resulting from blows may be found above but also within the HBL but not on the base of skull (Guyomarc'h *et al.*, 2010; Kranioti, 2015; Kratter, 1921; Kremer *et al.*, 2008; Kremer & Sauvageau, 2009).
Ehrlich and Maxeiner observed that lacerations from blows occur more often above the HBL than lacerations from falls (Ehrlich & Maxeiner, 2002; Maxeiner & Ehrlich, 2000).
The researches of Kremer *et al.* (Kremer *et al.*, 2008; Kremer & Sauvageau, 2009) show that injuries from blows are more often found above HBL, a laceration inside HBL is more in favor of a fall and a skull fracture inside HBL is found equitably in both etiologies.
The results of Guyomarc'h *et al.* (2010) show that blow can be distinguished from falls thanks to four criteria including the presence of fractures above the HBL.

This last point can be contradicted by the study of Ta'ala *et al.* (2006), we must pay attention to the context of trauma because this research revealed that cranial trauma was more likely caused by execution with a variety of blunt weapons applied to the back of the head/neck by Khmer rouge soldiers (Ta'ala *et al.*, 2006). Moreover, a victim can fall during an assault.
Rogers (1992) wrote that fractures in the basicranium could result indirectly from blows to the front of the head or through compression of the spine against the base of the skull.
According to Geserick *et al.* (2014), the HBL rule is not applicable to blows and falls from a height (including from stairs).
The HBL rule suggests that fractures from falls do not lie above the Hat Brim Line when some conditions are fulfilled (standing position of the individual before falling, flat floor without incline or stairs, falling from one's height, absence of intermediate obstacles) (Geserick *et al.*, 2014; Walcher, 1931).
Our results show that fractures on the basicranium and the vault occurred more frequently in falls cases than blows. Our previous research showed the same results (Henriques *et al.*, 2023).
According to research of Lefevre et al (2015) about differences in injuries caused by falls from less than 2.5 m high and homicides the incidence of cranial fractures in both etiologies were similar (Lefèvre *et al.*, 2015). In their study, the HBL did not be helpful int the distinction of falls and blows.
Many studies showed that fractures and injuries on the cranial vault and above the HBL could result from repeated falls, falls from a height or an impact against an edge or a corner as falls involving stairs (Ehrlich & Maxeiner, 2002; Fracasso *et al.*, 2011; Geserick *et al.*, 2014; Guyomarc'h *et al.*, 2010; Kremer *et al.*, 2008; Kremer & Sauvageau, 2009; Maxeiner & Ehrlich, 2000; Rowbotham *et al.*, 2018b; Walcher, 1931).
Once again, the use of the HBL rule should be used with caution as studies of the discrimination of falls and blows based only on fractures on the skull (cranial vault and basicranium).

The localization of fracture on the cranium is not discriminatory of one or another etiology but, according to our results, the presence of fracture on the 5th lumbar vertebrae, sacrum and proximal extremity of femur seems to be for blow cases.
According to the literature, thoracolumbar injuries occurs in fall from a significant height (Burke, 2012; Cooper *et al.*, 1995, 1993; Hsu *et al.*, 2003; Meldon & Moettus, 1995; Richter *et al.*, 1996; Samuels & Kerstein, 1993). However, fractures of the lumbar transverse processes may occur due to a direct blow to the lumbar area (Miller *et al.*, 2000).

The research of Mullingan and Talmi on 357 cases of assault find 2 patients with a lumbar spine transverse process fractures at the l5 level but no on the pelvis or on the femur (Mulligan & Talmi, 2009).

For many authors, femur fractures result from falls from heights (Burke, 2012; Court-Brown, 2015; Hollis *et al.*, 2015; Wedel & Galloway, 2014).

Just as sacral fracture frequently occurs in falls (Bydon *et al.*, 2014; Denis *et al.*, 1988; Maigne *et al.*, 2020; Meredith *et al.*, 2013; Rodrigues-Pinto *et al.*, 2017; Sabiston & Wing, 1986). However, it can occur with a direct blow and in some special cases like the one presented by Berryman and Saul (2015) presented a case of violent sexual assault with a fracture of the sacrum caused by a tire iron inserted vaginally.

4. Test of the new method in the distinction between falls and blows

The obtained data was used on the accepted for publication under minor revisions original paper:

Mélanie Henriques, Vincent Bonhomme, Marie-Dominique Piercecchi-Marti, Clémence Delteil, Ana Carballeira-Alvarez, Pascal Adalian, Eugénia Cunha. **Test d'une nouvelle méthode de distinction entre les chutes et les coups sur un échantillon de tomodensitométrie post-mortem**. Revue de Médecine Légale. 2023

4.1. Introduction

Etiology estimation of fractures is important in analyzing skeletal remains (Kranioti, 2015; Kremer & Sauvageau, 2009; Passalacqua & Fenton, 2012).

Some studies showed that a distinction between falls and blows could be made with a multi-criteria approach, but there is no reliable method to differentiate both etiologies. (Guyomarc'h *et al.*, 2010; Henriques *et al.*, 2023; Henriques *et al.*, 2023; Kremer *et al.*, 2008; Kremer & Sauvageau, 2009).

In a precedent article, we proposed a "revised" method. We highlighted that falls and blows could be predicted with a probability between 77% and 83% by four models based on the quotation of fracture on 28 bones, 12 anatomical regions, and baseline (age/sex) (Henriques *et al.*, 2023).

The revised method was established on living CT scans. It scores the presence/absence of fractures on 28 bones and 12 anatomical regions, with sex and age entered. This study evaluates the method's validity on a postmortem CT scan sample. Finally, the results were compared with the etiology stated in forensic reports to characterize the added value of this method revision.

4.2. Material and methods

We carried out a retrospective descriptive study from November 2009 to November 2020. All available cases in accordance with our selection criteria have been selected. We included adults aged 20 to 49 who had undergone a forensic autopsy for a trauma clearly identified during the first survey data (fall regardless of the height or blow with or without an object) and had undergone Post-Mortem Computerized Tomography scans (PMCT). A forensic pathologist made the case selection. Thus, the analysis of the scans was carried out by an independent anthropologist and blinded to the lesion mode.

The data collected on the autopsy report were made a posteriori and transmitted by the medical examiner.

PMCT records were extracted from the forensic report and the digital archiving systems of the Forensic Department of the Assistance Publique-Hôpitaux de Marseille (AP-HM, France). The sample comprised 47 anonymized patients aged between 20 and 49. The CT devices used were a Siemens Somatom definition (Siemens Healthineers Headquarters: Erlangen, Germany) and a General Electrics Optima CT 660 (GE Healthcare Headquarters: Chicago, IL, USA). Whenever possible, the body was in a supine position, arms resting along the body. Two acquisitions were made with 1mm sections: cervicocranial and from the cervical region to the feet.

We collected the following data on the autopsy reports: gender and age (later referred as 'baseline'), and whether the death was due to falls or blows. This last information was used only at the end of our study to perform blind tests.

Some bones were absent in the case of charring and/or putrefaction, so the fracture was encoded as non-available.

The method was built on the quotation of 372 types of fractures for 57 bones (skull and trunk) using two classifications, presented by the AO/OTA and Galloway and Wedel (2014), when possible (Galloway, 2014a, 2014b; Galloway & Wedel, 2014c, 2014d; Marsh *et al.*, 2007). We excluded 534 types and 29 bones to cope with absent and rare events (less than 5%). We tested various models of random forests, and the best ones were based on the binary coding of 15 types of fractures and 12 anatomical regions or 28 bones with or without baseline (age and sex). The quotation of the anatomical regions and the bones are complementary; one is more general, and the other more refined.

We register fracture (present or absent) on 28 bones (frontal, parietal, occipital, temporal, sphenoid, ethmoid, nasal, maxilla, zygomatic, mandible, scapula, 3rd to 10th rib, 12th thoracic vertebrae, 1st to 5th lumbar vertebrae, sacrum, coxal bone, and femur) and 12 anatomical regions (cranium, basicranium, cranial vault, face, mandible, ribs, scapula, thoracic vertebrae, lumbar vertebrae, coxal bone, sacrum, and femur).

The observations were performed using multiplanar reconstructions (MPRs), maximum intensity projection (MIP), and volume rendering (VR) reconstructions on Horos version 3.3.5®.

4.3. Statistical Analyses

The analyses were carried in the R environment version 4.1.3 (R foundation for statistical Computing, 2022, Vienna, Austria) with randomForest and KappaGUI R packages ('R', n.d.). We run the best four models of prediction tested and presented in Henriques *et al.* (2023) using the random forest algorithm (Henriques, Saliba-Serre, *et al.*, 2023). The four models are based on binary scoring (0: absence, 1: presence) of fracture on 28 bones with or without baseline (age and sex) and 12 anatomical regions with or without baseline. Thanks to implementing a simple tool (an online app), it is possible to directly obtain the inferred etiology and probabilities according to the four models.
The online tool is available at : fracture.cloud

Cohen's kappa was applied to assess the correct evaluations, that is, the agreement of the answer of our discrimination method and the real etiology based on the forensic report (conclusion of the autopsy which takes into account the findings of the investigation and the lesions found at the autopsy).

We randomly selected 30 individuals from the sample to assess the repeatability and reproducibility. Repeatability was tested by the same observer repeating the protocol twice several weeks apart; for reproducibility, a second observer applied the protocol once (both forensic anthropologists). The intra- and inter-error observers were evaluated using the same statistical test (Cohen's kappa).
Following Landis and Koch (Landis & Koch, 1977), a kappa value of < 0.2 was considered poor agreement, 0.21-0.4 fair, 0.41-0.6 moderate, 0.61-0.8 substantial, and more than 0.8 near-complete agreement.

4.4. Results

4.4.1. Observer agreement tests

The inter- and intra-observer errors were evaluated using Cohen's kappa (Table 11) (Cohen, 1960, 1968).
The inter-observer reliability of the scoring is good or even excellent for all bones and anatomical regions, with values higher than 0.61, except for the 8th rib for which the value was 0.44, indicating moderate reliability.

The intra-observer reliability of the scoring is excellent for all quotations, with values higher than 0.84, except for fracture on the 5th lumbar vertebrae, where the value was 0.76, indicating good reliability.

4.4.2. Prediction method

Of the 47 bodies, 35 were complete, and 12 presented missing bones (NA in Table 13); 39 were estimated to be falls and 8 to be blows.

Table 13: Scoring of fractures on the forensic sample (IND: individual, RCT: real context, ECT: estimated context, FT: frontal, TP: temporal, PT: parietal, OC: occipital, MX: maxilla, ET: ethmoid, ZY: zygomatic, SP: sphenoid, N: nasal, MD: mandible, SC: scapula, R3: rib3, R4: rib4, R5:rib5, R6: rib6, R7: rib7, R8: rib8, R9: rib9, R10: rib10, T12: thoracic vertebrae 12, L1:lumbar vertebrae 1, L2:lumbar vertebrae 2, L3:lumbar vertebrae 3, L4:lumbar vertebrae 4, L5:lumbar vertebrae 5, SA: sacrum, CO: coxal, FE: femur, BL: blow, FA: fall, F: female, M: male, 0: absence of fracture, 1: presence of fracture, NA: not available, TR: true, FL: false)

IND	RCT	ECT	SEX	AGE	FT	TP	PT	OC	MX	ET	ZY	SP	N	MD	SC	R3	R4	R5	R6	R7	R8	R9	R10	T12	L1	L2	L3	L4	L5	SA	CO	FE	RESULT
1	FA	FA	M	20	NA	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	TR
2	FA	FA	M	25	0	0	0	0	1	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	1	1	1	0	0	0	1	1	TR
3	FA	FA	M	29	1	1	1	1	NA	NA	NA	NA	NA	NA	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	TR
4	FA	FA	M	34	NA	1	1	1	NA	NA	NA	NA	NA	NA	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	TR
5	FA	FA	F	35	0	1	1	1	NA	1	NA	1	0	NA	NA	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	TR
6	FA	FA	M	46	0	NA	NA	NA	NA	0	NA	NA	0	NA	0	1	1	1	1	1	1	1	1	0	0	0	0	1	0	0	0	0	TR
7	BL	BL	F	46	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	TR
8	FA	FA	M	47	0	1	0	0	1	1	1	1	1	1	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	TR
9	FA	FA	F	48	0	1	0	1	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	TR
10	FA	FA	M	23	0	1	1	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	TR
11	FA	FA	F	24	0	0	0	0	1	1	0	0	1	0	1	1	1	1	0	1	0	0	0	1	1	1	1	0	0	0	1	0	TR
12	FA	FA	M	25	1	0	0	0	1	0	0	1	0	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1	TR
13	FA	FA	F	32	0	1	0	1	1	0	0	1	1	NA	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	TR
14	FA	FA	M	33	0	1	1	1	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	TR
15	FA	FA	F	34	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	0	TR
16	FA	FA	M	37	0	0	0	0	1	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	TR
17	BL	FA	M	43	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	FL
18	FA	FA	F	45	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	TR
19	FA	FA	F	47	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	TR
21	BL	FA	F	49	0	1	1	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	FL
22	BL	BL	M	34	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	TR
23	FA	FA	M	36	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	1	0	TR
24	BL	BL	M	26	0	1	NA	1	0	0	1	1	1	NA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	TR
25	BL	BL	M	43	0	0	0	0	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	TR
26	BL	FA	M	42	0	0	NA	NA	1	1	0	0	1	1	0	0	1	0	1	1	1	0	0	0	1	0	0	0	0	0	1	0	FL
27	BL	BL	M	34	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	TR
28	FA	FA	M	33	1	1	1	1	0	1	0	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	TR
31	BL	FA	M	47	0	0	0	0	1	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	FL
32	FA	FA	M	26	0	1	0	1	0	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	TR
33	FA	FA	M	37	1	1	1	1	1	NA	1	1	NA	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	TR
34	FA	FA	F	20	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	TR
35	FA	BL	M	33	1	1	1	0	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	FL
36	FA	FA	M	23	1	1	1	1	1	1	1	1	0	0	1	1	1	0	1	1	1	1	1	0	1	1	1	1	0	0	0	0	TR
37	BL	BL	M	34	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	TR
38	FA	FA	M	21	0	0	0	0	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	1	TR
39	FA	FA	M	29	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	0	0	0	TR
40	FA	FA	F	33	0	1	0	0	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	TR
41	FA	FA	M	22	0	1	1	1	0	0	0	1	0	0	1	0	1	1	1	1	1	1	1	0	1	1	1	1	0	0	0	0	TR
42	FA	FA	M	34	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	0	TR
43	FA	FA	F	39	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	NA	NA	NA	NA	NA	NA	NA	1	1	TR
44	FA	FA	M	29	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	TR
45	FA	FA	M	25	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	0	0	1	0	0	1	1	0	TR
46	BL	BL	M	48	NA	NA	NA	0	NA	NA	NA	NA	NA	1	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	TR
47	FA	FA	M	20	1	1	1	1	0	1	0	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	TR
48	FA	FA	F	48	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	0	0	0	0	TR
49	FA	FA	M	21	1	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	TR
50	FA	FA	M	44	NA	1	1	1	1	NA	1	NA	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	TR

According to the forensic reports, the sample comprised 36 falls and 11 blows.

Our method misclassified 5 subjects and, more precisely: 4 blow cases and 1 fall. Of the 5 subjects, 1 have missing data (20 %). The false predictions concerned 10.6 % of the sample: 4 males aged 33, 42, 43, and 49 years; and one female aged 49 (Table 14).

Table 14: Scoring of fractures on the misclassified cases by the method (IND: individual, RCT: real context, ECT: estimated context, FT: frontal, TP: temporal, PT: parietal, OC: occipital, MX: maxilla, ET: ethmoid, ZY: zygomatic, SP: sphenoid, N: nasal, MD: mandible, SC: scapula, R3: rib3, R4: rib4, R5:rib5, R6: rib6, R7: rib7, R8: rib8, R9: rib9, R10: rib10, T12: thoracic vertebrae 12, L1:lumbar vertebrae 1, L2:lumbar vertebrae 2, L3:lumbar vertebrae 3, L4:lumbar vertebrae 4, L5:lumbar vertebrae 5, SA: sacrum, CO: coxal, FE: femur, BL: blow, FA: fall, F: female, M: male, 0: absence of fracture, 1: presence of fracture, NA: not available)

IND	RCT	ECT	SEX	AGE	FT	TP	PT	OC	MX	ET	ZY	SP	N	MD	SC	R3	R4	R5	R6	R7	R8	R9	R10	T12	L1	L2	L3	L4	L5	SA	CO	FE
17	BL	FA	M	43	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
21	BL	FA	F	49	0	1	1	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
26	BL	FA	M	42	0	0	NA	NA	1	1	0	0	1	1	0	0	1	0	1	1	1	0	0	0	1	0	0	0	0	0	1	0
31	BL	FA	M	47	0	0	0	0	1	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
35	FA	BL	M	33	1	1	1	0	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The 4 misclassified blow cases are the individuals 17, 21, 26, and 31, briefly discussed as follows:

Individual 17 presented fractures on the mandible, scapula, and ribs (3^{rd} To 9^{th}).

Individual 21 had temporal, parietal, maxilla, sphenoid, mandible, and 1st and 2nd lumbar vertebrae fractures.

Individual 26 presented fractures on the maxilla, ethmoid, nasal, mandible, ribs (4^{th}, 6^{th}, 7^{th}, 8^{th}), 1^{st} lumbar vertebrae, and coxal bone.

Individual 31 had maxilla, nasal, and rib fractures (4^{th} to 6^{th}).

The fall case misclassified (individual 35) presents fractures on the frontal, temporal, parietal, maxilla, ethmoid, zygomatic, sphenoid, and the 4^{th} ribs.

The reliability between the estimated etiology and those written on forensic reports was substantial, with a Cohen's k-values of 0.67.

4.5. Discussion

When confronted with blunt force trauma, forensic experts are often asked to determine if the trauma is related to a fall or a blow. This discrimination remains a challenge, mainly because of unreliable methods. In this study, we tested the application of four prediction models, allowing us to give the probability of belonging to one etiology or another (falls or blows).

An excellent level of reliability in the intra- and inter-observer tests was found for all criteria except fracture on the 8th rib. This error may be due to a ranking error.

Cohen's k-values of this study show that the presented method is relevant in distinguishing between falls and blows.

Models applied to an independent forensic sample showed excellent etiology estimation for fall cases (97.2%) but misclassified 36.4% of blow cases.

A lack of classification in the category of cases of blows can also be explained by the fact that there are fewer cases of blows in the samples used for the method and its test. The model was trained less on this etiology than on that of falls.

The wrong estimation for the individual 35 can be explained by the fact that many bones of the face were fractured and that males aged between 30 and 39 were more involved in blows than in falls (Henn & Lignitz, 2004; Henriques *et al.*, 2023; Shepherd *et al.*, 1987; Strauch *et al.*, 2001; Wedel & Galloway, 1999).

For the others (blows misclassified), the age range and most fractured bones tend towards a fall rather than a blow (scapula, ribs, temporal, parietal, sphenoid, lumbar vertebrae, and coxal bone) (Burke, 2012; Cooper *et al.*, 1995, 1993; Court-Brown, 2015; Henriques *et al.*, 2023; Hsu *et al.*, 2003; Kani *et al.*, 2019; Meldon & Moettus, 1995; Restrepo *et al.*, 2009; Richter *et al.*, 1996; Samuels & Kerstein, 1993; Senekjian & Nirula, 2017; Talbot *et al.*, 2005; Wedel & Galloway, 2014).

In some forensic cases, there is no guarantee of full information. Some fractures may not be recorded, or some bones may just be missing, and difficult to assess whether they were broken or not when the person passed away. These elements were considered, quoted as not available (NA) and tested in this study.

Individual 26 has missing data, but only for two bones (parietal and occipital). As fractures on these bones occur more frequently in case of falls and the estimated context was fall, we do not believe there was an impact on this estimation of the etiology of fractures.

Within the 12 individuals with missing data, only 1 was misclassified, i.e., 8.3%.

This outcome indicates that the method is also suitable for fragmented or missing bones.

Chapter 5. General Discussion

General discussion

In the present study, we tried to see if skeletal patterns, morphologies, and the distribution of the skeletal fractures are characteristic of a certain type of etiology (falls or blows). The results of this exhaustive anthropological study of skeletal BFT resulting from falls and blows showed that fracture patterns and morphologies are characteristic of each etiology. This study developed an application to improve the analysis and interpretation of skeletal BFT in forensic anthropology.

1. Overview of findings

This study was conducted considering five aims (described in Chapter 1.6).

The first aim was to explore what is currently known about skeletal trauma in the distinction of falls and blows. To bring this forth, a comprehensive review of the literature on the BFT in the distinction between falls and blows was established in Chapter 2. This review found that the differentiation between falls and blows had been mainly based on the Hat Brim Line rule, a rule of 1931, where some conditions had to be fulfilled to apply (Walcher, 1931). Most forensic anthropology research showed that the HBL must be used carefully and in any case not as a unique criterion in distinguishing between falls and blows. Studies focused on this subject are composed of small samples or with a large gap between both etiologies. In the context of Daubert ruling Supreme (Lesciotto, 2015; US Supreme Court Decisions, 1993), these studies do not provide a reliable methodology for distinguishing falls and blows that can be used as evidence in court.

The second aim of this research was to attempt to mitigate this above shortcoming by developing a methodological approach to investigate and record the skeletal BFT resulting from falls and blows (Chapter 3). To investigate that, falls and blows of individuals aged 20 to 49 and presenting at least one fracture have been selected in the database from the hospitals of Marseille, Coimbra, and Nancy. Falls comprised falls from low height (≤ 3 m), from middle height (> 3 to ≤ 10 m), from high height (> 10 m), from its own height, from unknown height, and stairs. Blows comprised aggression with and without objects and unknown details. Fracture localization, patterns, and morphologies were observed from CT scans according to a binary coding and through the minimal number of fractures (quantitative and qualitative). We have removed all missing patterns and morphologies from the database.

The third aim was addressed using the methodology outlined above to investigate the fracture patterns and morphologies, the number, and localization for both etiologies: falls and blows. The data was investigated with logistic regression, multivariate statistics (the mean measure of divergence), and a supervised learning method used for classification (decision tree). As detailed in Chapter 4.1 and Chapter 4.2, these results provided generalized skeletal trauma findings, with localization, pattern, and morphology, which seem to allow the distinction between falls and blows. Given the diversity of the BFT mechanism, perfect discrimination is unrealistic, although there are exclusive patterns and morphologies to each etiology.

1.1. Falls

The investigation of skeletal trauma resulted from 235 cases of falls.

Hypothesis 1. There are specific fracture distributions characteristic of falls

- Fractures are more frequent and better distributed over the skeleton
- Simple fractures are more common in the face and the skull base.
- Multiple fractures are more frequent on the ribs and the lumbar vertebrae.
- The minimum number of fractures on the scapula, ribs, coxal bone, thoracic, and lumbar vertebrae is significantly more critical in falls.
- The absence of fractures on the mandible and face can differentiate falls from blows.
- The absence of a fracture on the mandible and the presence of a fracture on the face and the cranial vault can differentiate falls from blows.

Hypothesis 2: There are specific fracture morphologies characteristic of falls

- There were 246 fracture morphologies identified in this study. Of these, 43 showed significant associations.
- Half of the fall cases show the same pattern: no comminuted fractures on the coxal, no fracture of the ascending ramus of the mandible, no simple fracture of the maxilla, and no comminuted fractures on the mandible and the maxilla.
- Another pattern is the presence of comminuted fractures on the coxal.
- Another one is composed of no comminuted fractures on the coxal, no fracture of the ascending ramus of the mandible, no simple fracture of the maxilla, no comminuted fractures of the mandible, presence of comminuted fractures on the maxilla, and the presence of fracture of the sphenoid’s body.

1.2. Blows

The investigation of skeletal trauma resulted from 165 cases of blows.

Hypothesis 1. There are specific fracture distributions characteristic of blows

- Fractures on the skeleton are located more frequently on the face and the mandible.
- No fractures on the cervical vertebrae, clavicle, scapula, sternum, pelvic girdle, and upper extremity of the femur.
- Simple fractures show the prevalence for the same anatomical regions.
- Multiple fractures are more frequent in the face, mandible, and basicranium.
- The minimum number of fractures on the face and the mandible is significantly higher in blows.
- The presence of fractures on the mandible can differentiate blows from falls.
- The absence of a fracture on the mandible and the cranial vault and the presence of a fracture on the face can differentiate blows from falls.

Hypothesis 2: There are specific fracture morphologies characteristic of blows

- There were 246 fracture morphologies identified in this study. Of these, 8 showed significant associations.
- 20% of blow cases show the same pattern: the absence of comminuted fractures of the coxal bone, no fracture of the ascending ramus of the mandible, and a simple maxilla fracture.
- One of the blow's patterns is composed of the absence of comminuted fractures of the coxal and the fracture of the ascending ramus of the mandible.
- Another pattern is the absence of comminuted fractures of the coxal bone, no fracture of the ascending ramus of the mandible, no simple fracture of the maxilla, and comminuted fractures of the mandible.
- Another one is composed of the absence of comminuted fractures of the coxal bone, no fracture of the ascending ramus of the mandible, no simple fracture of the maxilla, no comminuted fractures of the mandible, presence of comminuted fractures of the maxilla and absence of fracture of the sphenoid's body.

1.3. The skull as a classical element of distinction

The distinction between falls and blows was often based on the skull lesions and their localization according to the Hat Brim Line (Guyomarc'h *et al.*, 2010; Kremer *et al.*, 2008; Kremer & Sauvageau, 2009; Walcher, 1931). Fracture patterns and morphologies resulting from these two etiologies have been previously documented, but there was considerable scope for extending these findings for further validation.

The skull remains an important anatomical region in distinguishing falls and blows. The face is the anatomical region of the skull more frequently affected by fractures in fall cases. The cranial vault is more fractured in fall cases. Concerning the basicranium, the frequency of occurrence of fractures is similar in both etiologies.

Finally, mandibular fractures are essential to strengthen the hypothesis of blows struck at the individual.

Yet, the skull is not the only element in the distinction between falls and blows.

1.4. Implementation of a method: the infracranial skeleton as a new element of distinction

Aim 4 of the research, as detailed in Chapter 4.3 and Chapter 4.4, was to create a new method and validate it on a forensic sample.

A new classification criterion based on a binary quotation of fractures on 12 anatomical regions or 28 bones with or without baseline (age and sex) was developed thanks to random forests (Chapter 4.3).

This new method shows that the infracranial skeleton can help distinguish falls and blows, not only the skull. (i.e. Hat Brim Line).

Fractures on the basicranium, vault, lumbar vertebrae, ribs, thoracic vertebrae, scapula, and coxal bone are more frequent in fall cases than in blows.

The localization of fracture on the cranium is not discriminatory to one or another etiology. However, according to our results, the fracture on the 5^{th} lumbar vertebrae, sacrum, and proximal extremity of the femur seems to be for blow cases.

The Daubert ruling requires objectivity and scientific rigor.

Repeatability and accuracy are important. The intra and interobserver error presented a substantial to perfect agreement for most variables, especially in the case of binary quotation.

The models of prediction created allow a prediction between 77 and 83%.

Then, to reach the fifth aim, we created an application available on https://grmoex.shinyapps.io/fracture/ whose interface is intuitive (Figure 51).

Figure 51: Interface of the application

We tested the application of the new methodology (based on four prediction models), on an independent forensic sample composed of 47 individuals (Chapter 4.4). Of these, 12 individuals presented missing information due to missing bones.

This application allows us to give the probability of belonging to one etiology or another (falls or blows) (Figure 51). Results showed excellent etiology estimation for fall cases (97.2%) but misclassified 36.4% of blow cases. Within the 12 individuals with missing data, only 1 was misclassified, i.e., 8.3%.

So, the presented method is relevant in distinguishing between falls and blows even for fragmented or missing bones, despite a lack of classification in the category of cases of blows.

2. Limitations

Several limitations of the present study concern the samples and variables.

First, the number of blows was relatively small compared to the fall cases. This fact impacted the results of prediction in this type of etiology. Indeed, the model was less trained on this etiology than on falls, so the prediction is less good, and the error rate is higher.

The second limitation is the lack of homogeneity in the details of the fracture context in medical reports.

The third limitation of this research was the completeness of the CT scans in the hospital (no full-body CT scans) and the sometimes quality of the medical imaging scans (i.e., CT resolution).

The fourth limitation is the lack of inter- and intra-observer analyses concerning fracture morphologies. In this research, skeletal trauma was only re-examined for 30 cases of the whole sample, and all fracture morphologies were present, this has prevented the calculation of the error rate.

Conclusion and future research directions

Conclusion and future research directions

Despite the variability of the BFT mechanism relative to the unique fall and blow events, there are significant fracture patterns and morphologies characteristic of these different etiologies. These findings will improve analyses and interpretations of skeletal trauma in falls and blows, allowing the forensic anthropologist to discuss the circumstances of trauma or death and consequently the implication of a third person. That said, the results of this research will be helpful for forensic anthropologists and pathologists in their tasks.

However, to strengthen this research, future directions include increasing the dataset's sample size, particularly blow cases.

To improve this research, we plan in the near future to :

- Identify and test fractures patterns and morphologies between detailed falls (i.e. falls from low height (≤ 3 m), from middle height (> 3 to ≤ 10 m), from high height (> 10 m), from its own height, and stairs and blows (aggression with and without objects).
- Identify and test fractures patterns and morphologies between low-energy falls and blows.
- Expand fracture patterns and morphologies to the appendicular skeleton and observe defensive fracture for example.
- Consider soft tissue and organ injuries to make a deepest comprehensive analysis.
- Increase the sample to compare the methodology between complete and incomplete bodies.
- Increase the sample of forensic cases.
- Increase the sample to have an equative one between males and females and include people not aged 20 to 49. This would expand research into child abuse and violence against women.

The detailed anthropological study of skeletal BFT identified fracture patterns and morphologies likely attributable to falls and blows. For the first time, an application can be used and give a probability to belong to one or another etiology, which can be an important element for the court.

These findings will then assist and improve the ability of forensic experts in the interpretation and circumstances of skeletal trauma.

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Annex I : Ethic application approval

UNIVERSIDADE DE COIMBRA
FACULDADE DE MEDICINA

COMISSÃO DE ÉTICA DA FMUC

Of. Refª **026-CE-2019**
Data 25/ 3 /**2019**

C/C aos Exmos. Senhores
Investigadores e co-investigadores

Exmo. Senhor
Prof. Doutor Duarte Nuno Vieira
Director da Faculdade de Medicina de
Universidade de Coimbra

Assunto: Projeto de Investigação no âmbito do Programa de Doutoramento em Antropologia Forense (refª CE-026/2019).

Candidato(a): Mélanie Henriques

Título do Projeto: *"Identificação da causa subjacente aos traumatismos resultantes de mecanismos contundentes"*.

A Comissão de Ética da Faculdade de Medicina, após análise do projeto de investigação supra identificado, decidiu emitir o parecer que a seguir se transcreve:

***"Parecer favorável"*.**

Queira aceitar os meus melhores cumprimentos.

O Presidente,

Prof. Doutor João Manuel Pedroso de Lima

HC

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Annex II : Published papers

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Research Article

Discrimination between falls and blows from the localization and the number of fractures on computed tomography scans of the skull and the trunk

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Abstract

The distinction between falls and blows is a common and difficult task in forensic sciences. One of the most often used criteria to address this issue is the hat brim line (HBL) rule, which states that fall-related injuries do not lie above the HBL. Some studies, however, have found that the use of HBL rule is not so relevant. This study assesses the aetiologies, the number of fractures, and their location on the skull and the trunk in a sample of 400 individuals aged 20–49 years, which were CT scanned after traumas. This may facilitate the interpretation of such injuries in skeletonized or heavily decomposed bodies in which soft tissues are no longer available. Our aim is to improve the distinction rate between falls and blows by combining several criteria and assessing their predictability. Skeletal lesions were analysed using retrospective CT scans. Cases selected comprise 235 falls and 165 blows. We registered the presence and the number of fractures in 14 skeletal anatomical regions related to the two different aetiologies. We showed that the HBL rule should be used with caution, but there is nevertheless a possibility of discussing the aetiology of blunt fractures. Possibly, parameters like the anatomical location and the number of fractures by region can be used to distinguish falls and blows.

Keywords: forensic sciences; blunt force trauma; falls; blows; skeletal fractures; CT scan

Introduction

One of the key roles of the forensic anthropologist, in collaboration with the pathologist, is to provide analysis and interpretation of skeletal trauma. They can afford an expert opinion on the death circumstances by inferring the mechanism of trauma from the skeletal fractures [1, 2].

Blunt force trauma (BFT) can be caused by a blunt object or a surface, as in transportation fatalities, falls, or interpersonal violence [3–5]. The highly variable nature of this type of trauma makes it complicated and difficult to interpret on the basis of the skeletal characteristics only.

Moreover, BFT is one of the most common injuries encountered by the forensic expert [1]. Therefore, the expert has to try to determine if the injury is induced by blows or related to a fall [1, 6]. To achieve this, the hat brim line (HBL) rule has often been used [6–9]. Nevertheless, this distinction remains a challenge, mainly because of a lack of objectivity and standardized methods.

This study aims to investigate whether circumstances of traumatic events have an influence on the fractures they create and on their distribution on the skeleton (skull and trunk).

If so, the second objective will be to check whether we can propose a method helping to define the aetiology of observed fractures.

Materials and methods

Study sample

A retrospective review of post-traumatic living individuals who were computed tomography (CT) scanned between 2008 and 2019 identified 400 cases of falls and blows, with at least one fracture. CT scans of these polytraumatized individuals were performed at the Assistance Publique-Hôpitaux de Marseille (AP-HM, France), the Centro Hospitalar e Universitário de Coimbra, and the Centre Hospitalier Regional et Universitaire de Nancy. These scans were anonymized and collected

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from the Picture Archiving and Communication System. The clinical management of the patients rarely required a full-body scan. According to medical indications of CT scans, the skeleton had to be considered in two parts: on the one hand, the cranium and the mandible; and, on the other hand, from the first cervical to the pelvis, without the appendicular skeleton (i.e. the spine, the thorax, the shoulder and pelvic girdles, and the upper end of the femur).

The scanner slices were 0.6 and 1.25 mm thick according to the acquisition protocol. We selected adults aged between 20 and 49 years old to have a certain homogeneity in the physicochemical properties of the bone.

Medical information for each of these cases, as well as case details relevant to the circumstances causing the BFT, was reviewed. Since this is a retrospective study, based on clinical management of a patient, not all information about the circumstances of fractures are systematically indicated. So, we have no data on the number of perpetrators or blows in blow injuries. Furthermore, whenever possible, the characteristics of the individuals were recorded. Details included the following data:

Circumstances of BFT:

- Date of the traumatic event
- Type of BFT (falls or blows)
- Date of CT scan
- Height of the fall (when the medical report gives this information)
- Blunt force object used (when the medical report gives this information)

Characteristics of the individuals:

- Age
- Sex

Following the standards of the National Consultative Ethics Committee for Health and Life Sciences, National Council of Ethics for the Life Sciences, and the Helsinki Declaration of 1975 concerning the privacy and confidentiality of personal data, all personal patient information was anonymized. Only the age, sex, and date of examination were known for each subject. All data were permitted by AP-HM for use in this study.

Variables

We selected 14 anatomical regions: basicranium, cranial vault, face, mandible, clavicle, scapula, sternum, ribs, cervical vertebrae, thoracic vertebrae, lumbar vertebrae, sacrum, coxal bone, and femur. Fractures on the basicranium comprise those of the cribriform plate of the ethmoid bone, the orbital plate of the frontal bone, the temporal bone, the sphenoid, and the occipital bone [10]. Given the definition of Cooper and Golfinos [10], and for the purposes of descriptive statistics, we only considered as vault elements: the frontal and parietal bones. The face is composed of the maxilla, the palatine, the vomer, the lacrimal bones, the nasal bones, and the zygomatic and the ethmoid bones without the cribiform plate. We grouped together cervical vertebrae and hyoid bone [10, 11].

Skeletal trauma was described for each individual as follows: the skeletal element and anatomical location of the injury (to investigate the distribution of the fractures on the body).

To record the presence of fractures in each anatomical region, we used a binary scoring (0, absence/1, presence); however, to take into account the number of fractures, we used a three-staged scores: 0: absence of fractures, 1: single fracture, and 2: two fractures or more.

Each individual was reviewed in the three anatomical planes (axial, coronal, and sagittal) using the window viewing presets for bone and this was adjusted manually on AW Workstation (AW server 2.0; GE HealthCare, Milwaukee, WI, USA) and Horos (version 3.3.5®; https://horosproject.org). The 3D volume renderings were also used to identify the fractures.

Statistical analyses

Fisher's exact tests were used to identify the association between two qualitative variables and specially the correlation between the fracture and the sex or the age group. Then, we used the mean measure of divergence (MMD), which is the most common procedure for calculating distances (the mean variance) from a set of nonmetric traits recorded in binary scoring [12–14]. MMD values of more than twice their corresponding standard deviations (SDs) were considered to be statistically significant and allowed us to consider that compared samples diverge.

To compare the mean numbers of fractures of the two aetiologies for each anatomical region, the Mann–Whitney *U* test was used.

Using the number of fractures on the different anatomical regions recorded in three different stages (absence/presence of one fracture/presence of two fractures and more), a decision tree was built to predict the aetiology of these fractures (falls/blows).

All statistical analyses were performed using the R Software® version 3.3.2 (R Foundation for Statistical Computing, Vienna, Austria). For all statistical tests, the significant level used was 0.05. We used {AnthropMMD} R package to calculate the distance between the two aetiologies regarding the presence of fractures in 14 different anatomical regions. {rpart} R package was used to build the decision tree.

To assess the repeatability, we randomly selected 30 individuals of the sample. The presence and number of fractures were observed twice in 14 anatomical regions by the same observer, which was trained on Horos version 3.3.5®. Inter- and intra-observer variations were evaluated using Cohen's Kappa coefficient with {KappaGUI} R package.

Results

Inter- and intra-observer errors

The inter- and intra-observer errors were evaluated using Cohen's Kappa (Table 1) [15, 16]. A table taken from Landis and Koch [17] was used for agreeing to evaluation (Table 2).

The results show a perfect and substantial agreement for all variables. The lowest value of Cohen's Kappa for the presence/absence of the fracture is 0.65 and for the scoring in three stages is 0.65, too.

Characteristics of the sample

Our sample includes 235 falls and 165 blows from three hospitals, which were CT scanned from January 2008 to August 2019. We observed 190 males (80.85%) and 45 females (19.15%) in fall cases and 152 males (92.12%) and 13 females (7.88%) in blow cases (Supplementary Table S1). Fisher's

Table 1. Inter- and intra-observer errors of the assessment of the presence and the number of fractures on 14 anatomical regions using Cohen's Kappa.

Anatomical region	Absence/presence		Absence/simple/multiple	
	Inter-observer	Intra-observer	Inter-observer	Intra-observer
Basicranium	0.71	1.00	0.72	1.00
Cranial vault	0.84	1.00	0.84	1.00
Face	0.90	0.90	0.91	0.82
Mandible	0.87	1.00	0.75	1.00
Clavicle	1.00	0.65	1.00	0.65
Scapula	0.84	1.00	0.84	1.00
Sternum	–	–	–	–
Ribs	0.72	1.00	0.68	0.93
Cervical V.	1.00	1.00	1.00	1.00
Thoracic V.	0.76	0.84	0.77	0.68
Lumbar V.	0.92	1.00	0.92	0.93
Sacrum	1.00	1.00	0.86	1.00
Coxal	1.00	0.87	1.00	0.87
Femur	1.00	1.00	1.00	1.00

–: The Kappa was not provided because the calculation made no sense. V.: vertebrae.

Table 2. Cohen's Kappa agreement (data from Landis and Koch [17]).

Kappa (*K*)	Strength of agreement
<0	Disagreement
0.00–0.20	Insignificant
0.21–0.40	Low
0.41–0.60	Middle
0.61–0.80	Good
0.81–1.00	Very good

exact test shows that the proportion of males significantly differs between the two aetiologies (80.85% *vs.* 92.12%, $P = 0.001$).

Regarding the age distribution, we found that adults aged 40–49 years involved in falls are more frequent (43.83%) than the two other age groups (27.66% for individuals between 30 and 39 years; 28.51% for the group of 20–29 years). Among the blow cases, almost the half (46.67%) was 20–29 years old, 33.33% of individuals aged 30–39 years and 20.00% of individuals aged 40–49 years (Supplementary Table S2).

Fisher's exact test shows a significant difference in the distribution of the individuals by age group between the two aetiologies ($P < 0.001$).

Skeletal fractures: circumstances, incidence, topography

An examination of the distribution and frequency of skeletal fractures showed that almost all skeletal elements were susceptible to fracture in both aetiologies (Tables 3 and 4, Figure 1).

Among the 235 falls, 34.89% of cases exhibited trauma to a single region and 65.11% of cases exhibited polytrauma. Among the 165 blows, 67.27% of cases exhibited trauma to a single region, and 32.73% of cases exhibited polytrauma (Table 3).

We observed that fractures occurred more frequently on the cranial vault, the basicranium, the clavicle, the scapula, the sternum, the ribs, the cervical vertebrae, the thoracic vertebrae, the lumbar vertebrae, the sacrum, the coxal bone, and the femur in falls, while fractures of the face (64.24%) and of the mandible (38.79%) occurred more often in blows (Table 4, Figure 1).

Table 3. Anatomical regions fractured by aetiology (*N*=400).

Aetiology	One AR fractured *n* (%)	More than one AR fractured *n* (%)
Falls ($n = 235$)	82 (34.89)	153 (65.11)
Blows ($n = 165$)	111 (67.27)	54 (32.73)

AR: anatomical regions.

Table 4. Presence of fractures by anatomical region in both aetiologies ($N = 400$).

Region	Falls ($n = 235$) *n* (%)	Blows ($n = 165$) *n* (%)	*P*-value
Basicranium	63 (26.81)	36 (21.82)	0.290
Cranial vault	47 (20.00)	16 (9.70)	**0.005**
Face	79 (33.62)	106 (64.24)	**<0.001**
Mandible	14 (5.96)	64 (38.79)	**<0.001**
Clavicle	9 (3.83)	0 (0.00)	**0.012**
Scapula	27 (11.49)	1 (0.61)	**<0.001**
Sternum	15 (6.38)	0 (0.00)	**<0.001**
Ribs	63 (26.81)	5 (3.03)	**<0.001**
Cervical V.	14 (5.96)	0 (0.00)	**<0.001**
Thoracic V.	47 (20.00)	3 (1.82)	**<0.001**
Lumbar V.	82 (34.89)	8 (4.85)	**<0.001**
Sacrum	49 (20.85)	0 (0.00)	**<0.001**
Coxal	54 (22.98)	2 (1.21)	**<0.001**
Femur	20 (8.51)	0 (0.00)	**<0.001**

P-value is associated with the Fisher's exact test; significant values are given in bold. V.: vertebrae.

Fractures of the face, the thoracic and lumbar vertebrae, the sacrum, and the coxal bone were significantly associated with sex. Fractures on the mandible, the ribs, and lumbar vertebrae were significantly associated with age (Table 5).

The MMD was calculated from the presence/absence of fractures in the 14 anatomical regions. The MMD value (0.341) is greater than twice the SD (0.004), indicating a significant difference between falls and blows.

Number of skeletal fractures

Concerning the minimum number of fractures in the 14 anatomical skeletal regions, we worked in two steps. First, we compared the mean number of fractures occurring in falls and blows (Table 6). The results show a significant difference between falls and blows based on the number of fractures on

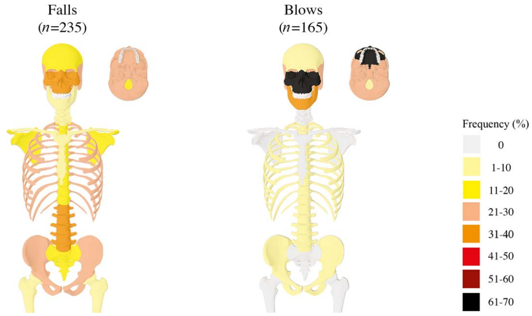

Figure 1. The frequency and distribution of fractures as related to the aetiology.

Table 5. Presence (%) of fractures by anatomical region, sex, and age ($N = 400$).

Region	Sex		*P*-value	Age (year)			*P*-value
	Female ($n = 58$)	Male ($n = 342$)		20–29 ($n = 144$)	30–39 ($n = 120$)	40–49 ($n = 136$)	
Basicranium	22.41	25.15	0.743	28.47	23.33	22.06	0.440
Cranial vault	15.52	15.79	1.000	19.44	15.00	12.50	0.279
Face	32.76	48.54	**0.032**	47.92	47.50	43.38	0.711
Mandible	12.07	20.76	0.152	27.08	21.67	9.56	**<0.001**
Clavicle	1.72	2.34	1.000	2.08	1.67	2.94	0.839
Scapula	5.17	7.31	0.782	4.17	6.67	10.29	0.135
Sternum	5.17	3.51	0.465	3.47	1.67	5.88	0.223
Ribs	18.97	16.67	0.705	9.03	18.33	24.26	**0.002**
Cervical V.	5.17	3.22	0.438	2.78	4.17	3.68	0.840
Thoracic V.	25.86	10.23	**0.002**	10.42	12.50	14.71	0.548
Lumbar V.	36.21	20.18	**0.010**	15.97	21.67	30.15	**0.018**
Sacrum	22.41	10.53	**0.016**	10.42	12.50	13.97	0.670
Coxal	24.14	12.28	**0.023**	10.42	20.00	12.50	0.075
Femur	8.62	4.39	0.188	4.86	5.83	4.41	0.882

P-value is associated with the Fisher's exact test; significant values are given in bold. V.: vertebrae.

Table 6. Comparison of the mean number of fractures by anatomical region according to the cause of the trauma.

Region	Falls		Blows		*P*-value (Mann–Whitney *U* test)
	[Min;max]	Mean (SD)	[Min;max]	Mean (SD)	
Basicranium	[0;7]	0.762 (1.629)	[0;8]	0.467 (1.182)	0.295
Cranial vault	[0;4]	0.366 (0.833)	[0;4]	0.212 (0.651)	**0.023**
Face	[0;8]	0.813 (1.614)	[0;6]	1.370 (1.639)	**<0.001**
Mandible	[0;2]	0.111 (0.439)	[0;2]	0.558 (0.768)	**<0.001**
Clavicle	[0;2]	0.060 (0.315)	–	–	–
Scapula	[0;2]	0.174 (0.514)	[0;1]	0.006 (0.078)	**<0.001**
Sternum	[0;2]	0.077 (0.311)	–	–	–
Ribs	[0;21]	1.362 (2.980)	[0;13]	0.230 (1.455)	**<0.001**
Cervical V.	[0;11]	0.157 (0.880)	–	–	–
Thoracic V.	[0;13]	0.545 (1.511)	[0;2]	0.030 (0.232)	**<0.001**
Lumbar V.	[0;12]	1.132 (2.007)	[0;7]	0.127 (0.709)	**<0.001**
Sacrum	[0;4]	0.391 (0.847)	–	–	–
Coxal	[0;2]	0.409 (0.776)	[0;2]	0.018 (0.174)	**<0.001**
Femur	[0;4]	0.149 (0.538)	–	–	–

In bold: significant values; –: no fracture was observed, so the comparison was not possible. V.: vertebrae; SD: standard deviation.

all anatomical regions except the basicranium. Fractures are more numerous in falls than in blows except for the face and the mandible.

Then, we synthesized the minimum number of fractures by a new scoring: 0: absence of fracture, 1: single fracture, and 2: more than two fractures.

Single fractures are more widespread in fall cases than in blow cases (Table 7, Figure 2A).

Fall cases exhibited widespread simple fractures with close frequencies (between 1.28% and 8.51%) even for the face, which presents 12.77% of fractures, and the basicranium, which presents 12.77% of fractures (Figure 2A, Table 7).

Table 7. Number (%) of fractures recorded in three stages present in the anatomical region, in both aetiologies ($N = 400$).

Region	Falls ($n = 235$)		Blows ($n = 165$)		*P*-value
	Simple (n, %)	Multiple (n, %)	Simple (n, %)	Multiple (n, %)	
Basicranium	30 (12.77)	33 (14.04)	17 (10.30)	19 (11.52)	0.529
Cranial vault	20 (8.51)	26 (11.06)	4 (2.42)	12 (7.27)	**0.012**
Face	30 (12.77)	42 (17.87)	28 (16.97)	66 (40.00)	**<0.001**
Mandible	4 (1.70)	10 (4.26)	32 (19.39)	32 (19.39)	**<0.001**
Clavicle	3 (1.28)	6 (2.55)	0 (0.00)	0 (0.00)	**0.018**
Scapula	13 (5.53)	14 (5.96)	1 (0.61)	0 (0.00)	**<0.001**
Sternum	12 (5.11)	3 (1.28)	0 (0.00)	0 (0.00)	**<0.001**
Ribs	7 (2.98)	56 (23.83)	0 (0.00)	5 (3.03)	**<0.001**
Cervical V.	5 (2.13)	9 (3.83)	0 (0.00)	0 (0.00)	**0.002**
Thoracic V.	16 (6.81)	31 (13.19)	1 (0.61)	2 (1.21)	**<0.001**
Lumbar V.	17 (7.23)	65 (27.66)	4 (2.42)	4 (2.42)	**<0.001**
Sacrum	16 (6.81)	33 (14.04)	0 (0.00)	0 (0.00)	**<0.001**
Coxal	12 (5.11)	42 (17.87)	1 (0.61)	1 (0.61)	**<0.001**
Femur	10 (4.26)	10 (4.26)	0 (0.00)	0 (0.00)	**<0.001**

P-value is associated with the Fisher's exact test; significant values are given in bold. V.: vertebrae.

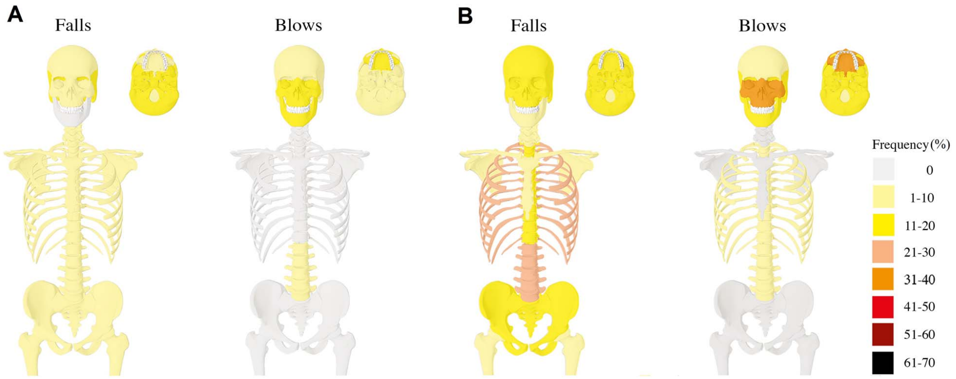

Figure 2. The frequency and distribution of simple (A) and multiple (B) fractures as related to the aetiology. Falls: $n = 235$; blows: $n = 165$.

In blow cases, only five anatomical skeletal regions are concerned by simple fractures, with a frequency > 1%: the basicranium (10.30%, $n = 17$), the cranial vault (2.42%, $n = 4$), the face (16.97%, $n = 28$), the mandible (19.39%, $n = 32$), and lumbar vertebrae (2.42%, $n = 4$) (Figure 2A, Table 7).

Fractures of the basicranium occurred more frequently in falls than in blows (12.77% *vs.* 10.30%) (Table 7, Figure 2A).

Fall cases exhibited again widespread multiple fractures (Table 7, Figure 2B). Multiple fractures are more frequent in lumbar vertebrae (27.66%, $n = 65$), then by decreasing frequency in ribs (23.83%, $n = 56$), face and coxal (17.87%, $n = 42$; for both), and sacrum and basicranium (14.04%, $n = 33$; for both), The mandible is more concerned by multiple fractures than simple ones (4.26% *vs.* 1.70%) (Table 7, Figure 2B).

Multiple fractures in blows are more localized and involved seven anatomical regions with a frequency > 1%: the face (40%, $n = 66$), the mandible (19.39%, $n = 32$), the basicranium (11.52%, $n = 19$), the cranial vault (7.27%, $n = 12$), the ribs (3.03%, $n = 5$), the lumbar vertebrae (2.42%, $n = 4$), and the thoracic vertebrae (1.21%, $n = 2$). No multiple fractures were observed on the clavicle, scapula, sternum, cervical vertebrae, sacrum, and femur (Table 7, Figure 2B).

A decision tree was built to identify the criteria playing a key role in the distinction between blows and falls (Figure 3). For this purpose, the number of fractures according to the three stages in 14 anatomical regions were used as independent variables of the model. The decision tree of our study integrated all 400 cases.

The three variables identified by the decision tree were the number of fractures on the mandible, on the face, and on the cranial vault. For each branch, the numbers of falls and blows are indicated (Figure 3). Given that 28 cases of blows and 54 cases of falls were misclassified, the misclassification rate with the leave-one-out method was equal to 20.5%.

Therefore, the decision tree correctly classified 79.5% of the total cases (77.02% (181/235) of falls and 83.03% (137/165) of blows). Perfect discrimination remains unrealistic, but the decision tree shows a strong discrimination potential between fall and blow cases using the number of fractures on the mandible, face, and cranial vault.

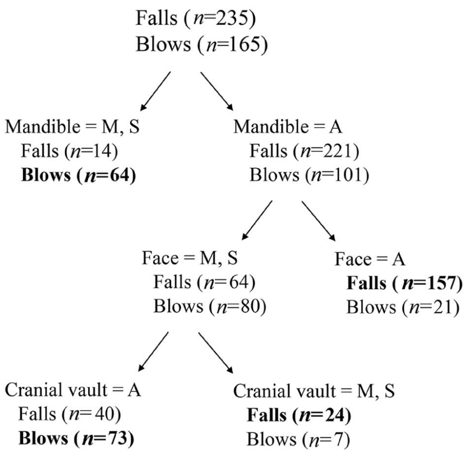

Figure 3. Decision tree (A: no fracture, S: simple fracture, M: multiple fractures).

Discussion

Repeatability

The results showed a perfect and substantial agreement for all the variables.

Fracture location, sex, and age

The presence of fractures by anatomical region, sex, and age (Table 5) showed that face fractures are found significantly more often for males. This is consistent with literature and with our sample distribution by sex and aetiology where males represent >90% of blow cases and with the fact that there is a significant tendency for face fractures to be caused by blows (Table 4) [18–20]. Concerning the thoracic and lumbar vertebrae, as well as the coxal and sacrum, there is a statistically significant difference showing that these bones are more often fractured in women (Table 5). Once again, this appears to be consistent with the fact that these bones are more often fractured in case of falls (Table 4) and that there is almost three times more women in our sample affected by falls. This prevalence of fracture can be explained by differences in bone structure between the sexes (influenced, among other things, by osteoporosis, pregnancy, or lactation) [21–25]. Finally, concerning age, Table 5 shows that the mandible is significantly less fractured when age increases, and this makes sense with the fact that mandible fracture is associated with blows (Table 4) and blows decreases with age [26–34]. On the contrary, Table 5 shows that ribs and lumbar vertebrae are significantly more often fractured with increasing age, and these bone fractures are associated with falls (Table 4) that increase with age (Figure 2A) [35, 36].

Skeletal fractures: circumstances, incidence, and topography

In this study, fractures occurred more frequently in falls for the postcranial skeleton, the basicranium, and the cranial vault. Conversely, the fractures of the face and the mandible were more frequently found in blows.

Falls

In fall cases, males are more frequent (80.85%) than females (19.15%) and the number of falls increases with age. Indeed, 43.83% of the population aged between 40 and 49 years (n = 103) compared to 28.51% of individuals aged 20–29.

These observations enabled us to highlight those fractures are more frequent and better distributed over the skeleton in fall cases. According to Kratter [37], falls cannot cause injuries of the vertex area nor the cranial vault (above the line binding the frontal eminence, the parietal eminence, and the external occipital protuberance) except in the case of a fall from a height or an impact against an edge or a corner [38, 39].

Simple fractures (i.e. single fractures) are more common in the face (12.77%) and the base of the skull (12.77%).

Multiple fractures are rather well distributed on the skeleton even if they present a lower frequent localization compared to the ribs (23.83%) and the lumbar vertebrae (27.66%).

The minimum number of fractures on the scapula, ribs, coxal bone, thoracic, and lumbar vertebrae is significantly more critical in falls. These results are perfectly consistent with the literature [3, 21, 39–46].

Blows

In blow cases, males are more frequent (92.12%) than females (7.88%) and the number of blows decreases with age. Indeed, 46.67% of individuals aged 20–29 years have at least one fracture compared to 20.00% of individuals aged 40 to 49. In 2001, Walker [26] noted that people involved in assaults tend to be young males.

Fractures on the skeleton are located on the face (64.24%) and the mandible (38.79%).

Simple fractures show prevalence for the same anatomical regions, presenting, respectively, 16.97% and 19.39%. Multiple fractures are more frequent in the face (40.00%), mandible (19.39%), and basicranium (11.52%).

The minimum number of fractures on the face and the mandible is significantly higher in blows.

These results are concordant with the literature since the head and face are the main rage focus of the perpetrator because these areas are psychologically linked to the victim's identity [47–50].

However, our results are divergent from Kratter [37] who showed that blows can cause injury in every region of the head with the exception of the base of the skull [38, 39].

Cranial vault

Our results showed that fractures in the cranial vault occurred more frequently in fall cases (19.57%, n = 46) than in blows (9.70%, n = 16).

Many studies showed that fractures and injuries on the cranial vault and above the HBL could not result from falls except in cases of repeated falls, falls from a height, or an impact against an edge or a corner; so they would be less frequent than in blow cases [6–9, 38, 39, 51, 52]. However, our results showed the opposite.

Basicranium

Our results showed that fracture on the basicranium occurred more frequently in fall cases (26.81%, n = 63) than in blow cases (21.82%, n = 36).

According to Kratter [37], blows can cause injury in every region with the exception of the base of the skull [39]. However, Rogers [53] wrote that basilar skull fractures could result indirectly from blows to the front of the head or through compression of the spine against the base of the skull. Our results confirmed these latest findings.

Face

Our results showed that fractures in the face occurred more frequently in blow cases (64.24%, n = 106) than in falls (33.62%, n = 79). Concerning blow cases, this result is concordant with those of many authors who said that one of the most commonly sustained injuries is to the face [18, 26].

According to Arabion et al. [54], the most frequent aetiology of facial fractures is falling, while for other studies, it is traffic-related [19, 54–57]. However, based on the study of Guyomarc'h et al. [7], one of the criteria pointing towards blows is the presence of facial fractures. Several authors agree that showing that violence is the most frequent cause of craniofacial fractures, and our results are consistent with this [20, 27, 58–63]. Our results showed that adult males are more frequently implied, whatever the aetiology is [18–20].

Mandible

Fractures on the mandible occur in 38.79% (n = 64) of blow cases and 5.96% (n = 14) of fall cases. Our results are similar to those of many studies showing that most fractures were caused by assault followed by falls [27–30] and are more frequent in young males (20–30 years old) [31–34].

Clavicle

Clavicle fractures were only observed in fall cases (3.83%, n = 9) with a predominance in males. These results are concordant with the literature. Clavicle fractures occur from sports, falls, and motor vehicle accidents [21, 40, 64–66]. According to Sirin et al. [67], this injury occurs more frequently in males than in females, with the highest incidence in the 20- to 30-year-old age group, which is similar to our study.

Scapula

Scapula fractures occur in 11.49% (n = 27) in fall cases and 0.61% (n = 1) in blows with a predominance in people aged 40 and 49 years (10.29%, n = 14). According to the literature, scapula fractures are uncommon and result from falls or motor vehicle incidents [3, 21, 40]. People aged 40–60 years are more implied, which is concordant with our results [3, 21, 68].

Rib

In our study, rib fractures are more frequent in fall cases (26.81%, n = 63) than in blow cases (3.03%, n = 5). People aged 40 and 49 years are more implied by this type of fracture.

According to the literature, rib fractures are common injuries and result from sports (stress fractures) and minor injuries (especially in elderly individuals) [69, 70] or from homicidal actions, particularly stomping on the chest of a prone victim or a direct blow or kicking and from cardiopulmonary resuscitation [64, 71]. Fractures in the upper zone of the thoracic cage (one to fourth ribs) require high-velocity trauma [69]. Rib fractures are complex and are an essential indicator of trauma severity (morbidity and mortality increase with increasing numbers of ribs fractured) [69, 72–74].

Sternum

In our sample, sternum fractures only occur in fall cases (6.38%, n = 15). According to the literature, sternal fractures can result from motor vehicle accidents, contact sports, falls, and assaults [72, 74, 75].

Vertebrae

In our sample, there are no cervical fractures in blows, but in falls they have a frequency of 5.96% (n = 14). Overall, spinal fractures frequently occur in falls [40]. Cervical fractures are frequent in motor vehicle accidents, sporting accidents, and assaults with weapons [21]. During an attack, these kinds of fractures are more due to the fall [76–78].

In our sample, fractures on thoracic and lumbar vertebrae are more frequent in fall cases than in blows. According to the literature, thoracolumbar injuries are due to motor vehicle accidents and fall from a significant height [21, 41–46].

The thoracolumbar fractures are more frequent in females. These significant differences between males and females can be explained by structural and kinetic differences, "probably an evolutional allowing female to carry their fetus while standing in an upright position" [22]. Indeed, females display a lumbar hyperlordosis, a thoracic hypokyphosis and a lesser lumbar range of motion in flexion–extension [22]. These elements limit the prevalence of cervical spine fracture and can be the cause of lumbar spine fractures in females. Moreover, according to many authors, during pregnancy and lactation, females lose 3%–10% of trabecular bone [79].

Sacrum

Our results show that sacral fractures only occur in fall cases (20.85%, n = 49) and are more frequent in females (22.41%, n = 13).

According to the literature, fractures of the sacrum can be caused by a stress fracture or insufficiency fracture [53, 80]. This last fracture occurs within normal stress on the bone. The bone can be weakened by pregnancy and lactation, radiation therapy, rheumatoid arthritis, osteoporosis (which can also be caused by some medications or diseases), demineralization in elderly patients, and postmenopausal females [21, 23–25]. Sacral fracture frequently occurs in motor vehicle accidents and falls and are more frequent in females [81–85].

Coxal bone

In our study, fractures of the coxal bone are more frequent in falls (22.98%, n = 54) and in females (24.14%, n = 14).

Pelvic fractures in adults are associated with significant morbidity and mortality [3, 86]. Pelvic fractures are most common in young adult males and older males and females [87, 88]. The prevalence of pelvic fractures is male for Pereira et al. [89] and female for Buller et al. [90], Sanders et al. [91], and Melton et al. [92]. According to Balogh et al. [93], pelvic fractures in males occur more frequently in high-energy accidents (motor vehicle accidents), and for females, these occur in low-energy injuries. Pelvic fractures are common in motor vehicle accidents, falls, and sport-related accidents [3, 21, 40].

Femur

This study shows that fractures of the proximal femur only occur from falls (8.51%, n = 20).

As for the coxal bone and sacrum, insufficiency fractures can occur on the proximal extremity of the femur [94]. In young adults, femur fractures result from motor vehicle accidents, falls from heights, or sports [3, 21, 40, 95].

The skull: an important anatomical region in the distinction between falls and blows?

A significant amount of research has been devoted to understanding the biomechanics of fractures by powerful forces [96–98], but few studies have focused on the evaluation of the origin of the trauma by analysing the fracture location and morphology [6–9, 51, 99–102]. This is why it is necessary to deepen our knowledge in this field. Blunt force injuries located in the cranium and in the trunk are preferentially associated with interpersonal violence. They are often linked with the manner and cause of death, which makes their examination crucially important in the medicolegal investigation of death circumstances [4, 5, 48–50, 99, 103–105].

One of the first authors who tried to distinguish between falls and blows based on the skull lesions, in 1905, was Richter [106]. He highlighted the attention that must be paid to the amount of skin bruises and their location. If there are particular reasons for repeated falls, if the bruises are numerous and are located in regions that cannot be involved in cases of a fall (the cranial vertex), we can hypothesize that the child is beaten.

In 1921, Kratter's researches (as cited by Fracasso in 2011) showed falls can cause injuries to the vertex area and cranial vault when the fall was from a great height or if there was an impact with an obstacle during the fall [38, 39].

Regarding a similar line, Walcher, in 1931, created the HBL rule which says that fall-related injuries do not lie above the HBL when some conditions are fulfilled (standing position of the individual before falling, flat floor without incline or stairs, falling from one's height, and absence of intermediate obstacles), but the rule is not applicable for small children [38, 52].

Nowadays, the HBL is defined as the area above the Frankfort horizontal plane, which is located between the line passing through the glabella (G-line) and the line passing through the centre of the external auditory meatus (EAM-line) [51] (Figure 4).

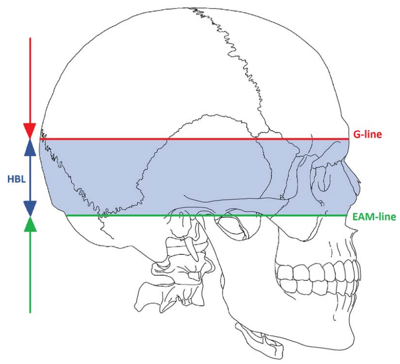

Figure 4. The hat brim line (HBL), area located between the G-line (the superior margin) and EAM-line (the inferior margin).

The use of the HBL rule in the distinction between falls and blows is controversial. Despite this, some studies have used this rule when observing skull fractures and skin lesions.

The few studies that have compared falls and blows cases in relation to the HBL to determine the validity of this rule are those cited below.

Ehrlich and Maxeiner [8, 9], Kremer et al. [6, 51], and Guyomarc'h et al. [7] undertook studies to distinguish between falls and blows in blunt head traumas. Ehrlich and Maxeiner [8, 9] studied 254 falls (203 on a flat surface, 51 downstairs) and 51 blows. They observed that lacerations from blows occur more often above the HBL (55%) than lacerations from falls (33%).

Kremer et al. [6, 51] focused on the location of cranial fractures and number of lacerations. In Kremer et al. [51], 36 falls (23 from one's own height, 13 downstairs) and 44 blows were observed. The results showed that injuries from blows are more often found above HBL, although this rule should be used with caution. In Kremer et al. [6], 50 falls were observed (29 from one's height, 21 downstairs) and 64 interpersonal violence with a blunt weapon. The study confirmed that injuries inflicted by blows are often situated above HBL, a laceration inside HBL is more in favour of a fall (66.7%), and a skull fracture inside HBL is found equitably in both aetiologies.

Guyomarc'h et al. [7] described the number and length of lacerations on the entire skull, type of skull fractures, location of injuries, and the presence or the absence of postcranial injury in 50 cases of falls (29 from own height, 21 downstairs) and 63 cases of homicidal blows. The results showed a strong discrimination potential between fall and blow cases with four criteria, including the presence of fractures above the HBL (in favour of blows).

The authors confirmed that HBL has to be used carefully and not as a single criterion in the distinction between falls and blows. Perfect discrimination remains unrealistic, and before we can quickly and accurately distinguish falls from blows, there is a lot more work to be performed. Moreover, we have to be careful as some studies have a weak sample.

Besides, we find more fractures related to falls than to blows above this HBL, so the use of the HBL rule is limited. In both cases, the face is the anatomical region of the skull which is more frequently touched by fractures. Concerning the basicranium, the frequency of occurrence of fractures is similar in both aetiologies. Finally, the presence of fractures on the mandible is an important element to strengthen the hypothesis of blows struck at the individual.

The decision tree proposed in our study showed the importance of fractures located on the mandible, on the face, and on the cranial vault because it allows a distinction between blows and falls. By using this tree on our study sample to predict the aetiology of fractures, and taking care to use a "Leave One Out" procedure, the decision tree correctly classified 79.5% of the cases.

Some of these anatomical regions were already used in the "combined criteria tools" of Guyomarc'h et al. [7], which considered the number of scalp lacerations, the scalp laceration length, the vault fracture type, and the presence or absence of facial fractures. Their decision tree classified 82% of falls and 93.7% of blows correctly.

However, it should be noted that these two studies did not take into account certain parameters that can affect bone fractures (such as one's character or region). Indeed, some authors have shown that the risk of fracture and their location are related to ethnicity [107–109].

Conclusion

It seems that the HBL rule should be used with caution, but this preliminary stage of our work has shown that there is nevertheless a possibility of discussing the aetiology of blunt fractures, with the presence of fractures either on the cranium alone, or on the cranium and the postcranium.

We can use parameters like the anatomical location and the minimum number of fractures by anatomical regions to distinguish falls and blows even if several other parameters remain to be integrated (as the typology of fractures).

Ultimately, the goal is to develop a rating system that allows us to further refine the prediction of the aetiology of blunt fractures found during the postmortem study of skeletons.

However, our study showed that the skull is not the only anatomical region showing a significant difference between falls and blows.

Indeed, the postcranial regions play a role in the distinction of the two aetiologies, and more particularly, scapula, ribs, coxal bone, and thoracic and lumbar vertebrae.

Finally, we are perfectly aware that this is a preliminary study and that, for instance, there might be a relationship between the location of fractures caused by blows and with one's ethnicity, character, and region. These results should be qualified and we look forward to extend our sample to other populations.

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Authors' contributions

Mélanie Henriques carried out the study, performed the statistical analysis, and drafted the manuscript; Bérengère Saliba-Serre participated in the statistical analysis and revised the manuscript; Laurent Martrille contributed materials from Nancy and revised the manuscript; Alain Blum contributed materials from Nancy; Kathia Chaumoître contributed materials from Marseille; Paulo Donato and Nuno Campos contributed materials from Coimbra; Eugénia Cunha and Pascal Adalian both participated in the study's design and coordination and revised the manuscript. All authors contributed to the final text and approved it.

Compliance with ethical standards

The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Ethics Committee of Faculdade de Medicina da Universidade de Coimbra, Portugal (protocol code: 026-CE-2019 and date of approval: 25/03/2019).

Data availability

The data for this study are kept by the first author.

Disclosure statement

Eugénia Cunha initial holds the position of Editorial Board Member for *Forensic Sciences Research* and is blinded from reviewing or making decisions for the manuscript.

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biology

Article

Blows or Falls? Distinction by Random Forest Classification

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Simple Summary: In forensic anthropology, skeletal trauma analysis can assist pathologists in determining the circumstance, cause, and manner of death. Determining whether the trauma is related to falls or induced by homicidal blows is often asked in relevance to legal issues. The hat brim line rule (HBL) is one of the most commonly used methods. The rule says that fractures resulting from blows may be found above and within the HBL, not on the skull's base. Recent studies have found that the HBL rule must be used carefully, and postcranial skeletal trauma could be useful in this distinction. Evidence presented in court must follow Daubert's guidelines for validity and reliability (evidence validated; error rates known; standards available; findings should be peer-reviewed and accepted by the scientific community). In this study, we assessed skeletal fracture patterns resulting from both etiologies. We tested various models for the method; the best one was based on the binary coding of 12 anatomical regions or 28 bones with or without baseline (age and sex). The results show the possible identification of the etiology in 83% of the cases. This method could be helpful for forensic experts in the interpretation of bone fractures.

Abstract: In this study, we propose a classification method between falls and blows using random forests. In total, 400 anonymized patients presenting with fractures from falls or blows aged between 20 and 49 years old were used. There were 549 types of fractures for 57 bones and 12 anatomical regions observed. We first tested various models according to the sensibility of random forest parameters and their effects on model accuracies. The best model was based on the binary coding of 12 anatomical regions or 28 bones with or without baseline (age and sex). Our method achieved the highest accuracy rate of 83% in the distinction between falls and blows. Our findings pave the way for applications to help forensic experts and archaeologists.

Keywords: forensic science; blunt force trauma; falls; blows; skeletal fractures; CT scan; random forests

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1. Introduction

Considerable research has been conducted to attempt to distinguish between falls and blows. The most cited approach is the hat brim line (HBL) rule, which has often been simplified as fractures resulting from falls located within the HBL. In contrast, fractures resulting from blows may be found above and within the HBL, not on the skull's base. Recent studies have found that the HBL rule must be used very carefully because their results do not match the definition [1–4].

We previously showed that the discrimination between falls and blows could be discussed by the site and the number of fractures found on the skull and the trunk [4].

This study primarily aimed to find additional valuable criteria (i.e., the type of fractures) in the distinction of both etiologies. Furthermore, we aimed to test various models with random forests by selecting and combining criteria with the highest predictability rates.

Ion approval

2. Materials and Methods

2.1. Dataset Description

Following the standards of the National Consultative Ethics Committee for health and life sciences (CCNE), the National Council of Ethics for the Life Sciences (CNECV), and the Helsinki Declaration of 1975 concerning the privacy and confidentiality of personal data, our dataset consisted of 400 anonymized patients presenting with fractures from falls or blows and between 20 and 49 years old. The CT scans of our sample were collected from the PACS (Picture Archiving and Communication System) in the Assistance Publique-Hôpitaux de Marseille (AP-HM, Marseille, France), the Centro Hospitalar e Universitário de Coimbra, and the Centre Hospitalier Regional et Universitaire de Nancy. According to the acquisition protocol, the scanner slices were 0.6 mm and 1.25 mm thick. Each individual was reviewed in the three anatomical planes (axial, coronal, and sagittal) using the window viewing presets for bone and adjusted manually on AW Workstation (AW server 2.0, GE HealthCare, Milwaukee, WI, USA) and Horos® (version 3.3.5, © 2021 Horos Project). Three-dimensional volume renderings were also used to identify the fractures.

The following variables were available: sex and age (later referred to as baseline) on the one hand and the 549 types of fractures for all 57 bones on the other. We used two classifications, AO/OTA and Galloway, Wedel 2014 (Broken Bones), when possible. Otherwise, we observed the presence/absence of a fracture in different parts of a bone [5,6]. The observations were performed using multiplanar reconstructions (MPRs), maximum intensity projection (MIP), and volume rendering (VR) reconstructions on Horos version 3.3.5®.

To cope with absent and rare events (less than 5%), such as fractured bones with low frequencies, we excluded 534 types and 29 bones. The final dataset included 15 types of fractures and 28 bones.

On the 28 remaining bones, 12 anatomical regions were defined: cranium, basicranium, cranial vault, face, mandible, scapula, ribs, thoracic vertebrae, lumbar vertebrae, sacrum, coxal bone, and femur.

2.2. Inter- and Intra-Observer Errors

To assess the repeatability, we randomly selected 30 individuals from the sample. Inter- and intra-observer variations were evaluated using Cohen's kappa coefficient with the {KappaGUI} R package.

2.3. Random Forest Approach

We aimed to predict the circumstances of observed fractures, i.e., a blow or a fall, using the available etiology. We chose to use the random forest approach because it is an appropriate supervised learning technique when the number of observations is lower or of the same magnitude as the number of variables [7,8]. It is also adapted to classification problems which include qualitative and quantitative variables.

2.4. Statistical Environment

All analyses were performed in the R 4.1.3 statistical environment [9], using the following packages: randomForest to model and predict using random forests [10]; pROC to calculate ROC curves [11]; and tidyverse for general data manipulation, programming, and data visualization [12].

2.5. Model Selection

As implemented in randomForest [10], the random forest algorithm comes with three internal parameters: mtry (the number of variables randomly sampled as candidates at each split), nodesize (the minimum size of terminal nodes), and ntree (the number of trees to calculate). Additionally, our dataset enabled different approaches: which data to use (bones, typology, anatomical region, and whether or not to include the sex/age of the patient) and the metric of the data (quantitative, ternary, or semi-qualitative {0, 1, 2+} or binary {0/1}).

Altogether, these five parameterizing dimensions enable many different models to be trained. The successive steps described below aim to reduce this number to a few accurate models.

2.6. Grid Search for Hyper Parameters Optimization

We first explored the sensibility of random forest parameters and their effects on model accuracies. We used a grid search approach on the five dimensions. The mtry parameter was the only one that varied between datasets. A default and sensible value for these parameters is the square root of the number of variables used, rounded to the lower integer. We circumvented this by defining mtry_k as simply a multiplicative factor to this default value. For example, for a 36-variable dataset, mtry_k = 1 leads to mtry = 6, mtry_k = 0.5 results in mtry = 3, mtry_k = 2 produces mtry = 12, etc.

The full combination of models tested was: mtry_k {0.25, 0.5, 1, 2, 4}; nodesize {1, 2, 5, 10}; ntree {101, 501, 1001, 2001}; metric {quantitative, ternary, binary}; datasets {baseline alone, bone, bone + baseline, type, type + baseline, anatomical region, anatomical region + baseline}. This resulted in 1680 models.

The dataset was randomly partitioned into 300 patients for the training set and 100 patients for the testing set. The latter was never seen by the model while training. To estimate parameter elasticity and the impact of such partitioning, we repeated the entire grid search process for ten different sets of partitions, following the same scheme.

2.7. Benchmarking Models with Fixed Internal Parameters

After selecting random forest internal parameters, we ran the same models and explored the structure of their predictions, including the contrast between the error obtained on the train versus on the test partition.

Model selection was also performed here to select both the dataset and metric to use. Accuracy, i.e., low error, was the first criterion. We also considered how the models were generalized: ideally, we would expect similar errors to indicate that the model was not overfitting training data. Finally, parsimony helped us select between metric: for comparable model performance, the more straightforward (e.g., binary versus ternary), the better.

2.8. Class-Wise Predictions for the Final Models

Finally, on the four final models, we explored their results as regards their prediction in terms of etiology alone, etiology for each sex, and etiology for age classes. To ease graphical interpretation, we binned the continuous age variables into 10-year bins ranging from 20 to 49.

2.9. Variable Importance and Their Sign

Variable importance, i.e., how the bone/anatomical results influence the classification task, was calculated. We also attempted signing these contributions towards either blow or fall. This could not be retrieved directly with random forests; however, the marginal distributions of occurrence for each bone/region enabled accurate estimates to be performed. The proportions of broken bones/regions were calculated and adjusted for the overall sample size of each etiology; otherwise, it was unbalanced.

2.10. Predicting New Patients

Regarding new individuals, there is no guarantee of complete information. Some fractures may not be recorded, and some bones may just be missing, making it difficult to assess whether they were broken or not when the person passed away. In forensic contexts, there are many cases where information about the context is unknown and where it is paramount to establish the manner of death, i.e., whether it was accidental, homicide, or suicide.

3. Results

3.1. Inter- and Intra-Observer Errors

The inter- and intra-observer errors were evaluated using Cohen's kappa (Table 1) [13,14]. A table taken from Landis and Koch [15] was used for agreeing to the evaluation (Table 2).

Table 1. Inter- and intra-observer errors in the assessment of the presence and the number of fractures in fourteen anatomical regions using Cohen's kappa.

Localization	Absence/Presence		Absence/Simple/Multiple		Quantitative	
	Inter-Observer	Intra-Observer	Inter-Observer	Intra-Observer	Inter-Observer	Intra-Observer
Basicranium	0.71	1	0.72	1	0.60	0.78
Cranial Vault	0.84	1	0.84	1	0.84	1
Face	0.9	0.9	0.91	0.82	0.82	0.82
Mandible	0.87	1	0.75	1	0.75	1
Scapula	0.84	1	0.84	1	0.84	1
Ribs	0.72	1	0.68	0.93	0.41	0.57
Thoracic V.	0.76	0.84	0.77	0.68	0.78	0.54
Lumbar V.	0.92	1	0.92	0.93	0.71	0.75
Sacrum	1	1	0.86	1	0.59	0.86
Coxal	1	0.87	1	0.87	1	1
Femur	1	1	1	1	1	1
Frontal	0.78	1	0.79	1	0.79	1
Parietal	1	1	1	1	1	1
Occipital	1	1	1	1	1	1
Temporal	0.84	1	0.84	1	0.69	1
Sphenoid	0.84	1	0.84	0.72	0.84	0.72
Ethmoid	1	1	1	1	1	1
Nasal	1	1	1	1	1	1
Maxilla	0.71	0.84	0.72	0.84	0.72	0.84
Zygomatic	1	1	0.86	0.86	0.86	0.86
Mandible	0.87	1	0.75	1	0.75	1
Scapula	0.84	1	0.84	1	0.84	1
Rib3	0.61	1	0.5	1	0.50	1
Rib4	0.76	1	0.77	1	0.77	1
Rib5	1	1	1	1	0.86	1
Rib6	0.84	0.87	0.84	0.88	0.69	0.88
Rib7	0.67	0.81	0.68	0.83	0.68	0.83
Rib8	0.44	0.91	0.48	0.84	0.48	0.84
Rib9	0.90	0.90	0.82	0.91	0.73	0.82
Rib10	0.76	0.89	0.54	0.89	0.54	0.89
VTH12	0.64	1	0.64	1	0.64	1
VLO1	1	1	0.90	0.90	0.81	0.81
VLO2	1	1	1	0.90	1	0.90
VLO3	0.71	1	0.71	1	0.71	1
VLO4	0.84	0.87	0.84	0.87	0.84	0.87
VLO5	0.71	0.76	0.71	0.76	0.71	0.76
Coxal	1	0.87	1	0.87	1	0.87
Sacrum	0.84	1	0.84	1	0.84	1
Femur	1	1	1	1	1	1
Simple fracture zygomatic process of Temporal	0.78	1	0.78	1	1	0.78
Petrous portion of Temporal	0	1	0	1	0	1
Linear fracture of Sphenoid	1	0.78	1	0.78	1	1
Body of Sphenoid	1	1	1	1	1	1
Ethmoid	1	1	1	1	1	1
Nasal	1	1	1	1	1	1
Simple Fracture Maxilla	0.65	0.65	0.65	0.65	0.65	0.65
Comminuted fracture Maxilla	0.78	1	0.78	1	0.78	1
Ascending ramus of Mandible	1	1	1	1	1	1

Table 1. *Cont.*

Localization	Absence/Presence		Absence/Simple/Multiple		Quantitative	
	Inter-Observer	Intra-Observer	Inter-Observer	Intra-Observer	Inter-observer	Intra-Observer
Comminuted fracture of Mandible	0.65	1	0.65	1	0.65	1
Transverse process of VL1	1	1	1	1	1	1
Transverse process of VL2	1	1	1	1	1	1
Transverse process of VL3	0.63	1	0.63	1	0.63	1
Transverse process of VL4	0.78	0.84	0.78	0.84	0.78	0.84
Comminuted fracture of Coxal bone	1	1	1	1	1	1

Table 2. Cohen's kappa agreement (Data from Landis and Koch (1977)).

Kappa (k)	Strength of Agreement
<0	Disagreement
0.00–0.20	Insignificant
0.21–0.40	Low
0.41–0.60	Middle
0.61–0.80	Good
0.81–1.00	Very good

The results showed a perfect and substantial agreement for most variables with a binary quotation. Only the eighth rib exhibited a moderate inter-observer error, with a kappa value of 0.44. Only fractures in the petrous portion of the temporal bone have a sight error inter-observer (0).

The results showed a perfect and substantial agreement for most variables with a ternary quotation. Only the third, eighth, and tenth ribs showed moderate inter-observer error, with kappa values of 0.5, 0.48, and 0.54, respectively. Only fractures in the petrous portion of the temporal bone exhibited a slight inter-observer error (0).

The results show a perfect and substantial agreement for most variables with a quantitative quotation. Other variables showed a moderate inter-observer error, between 0.48 and 0.60, for fractures in the basicranium, ribs (third, eighth, and tenth), and sacrum. Other variables showed a moderate intra-observer error between 0.54 and 0.57 for ribs and thoracic vertebrae fractures.

The best reproducibility was in all types of quotation of the type of fractures, the ternary quotation of fractures in anatomical regions, and, more generally, the binary quotation.

3.2. Parameter Optimization

As shown in Figure 1, we ran each model several times for different values of the mtry_k, nodesize, and ntree parameters. For each run, we measured the model's error rate (i.e., 1-accuracy).

For each box figure, the green box indicates that the central 50% of data lies in this section; the bold bar is the median value; the upper and lower black bars are the greatest and least values, excluding outliers; and finally, the black crosses represent the outliers.

As seen from the box figure, all rating models had similar thresholds for the error rate despite the variations in the mtry_k, nodesize, and ntree parameters.

However, notably, the mtry_k = 1, nodesise = 5, and ntree = 501 parameters showed a lower error rate than models based on the observation of fractures in the bone with or without baseline and anatomical regions.

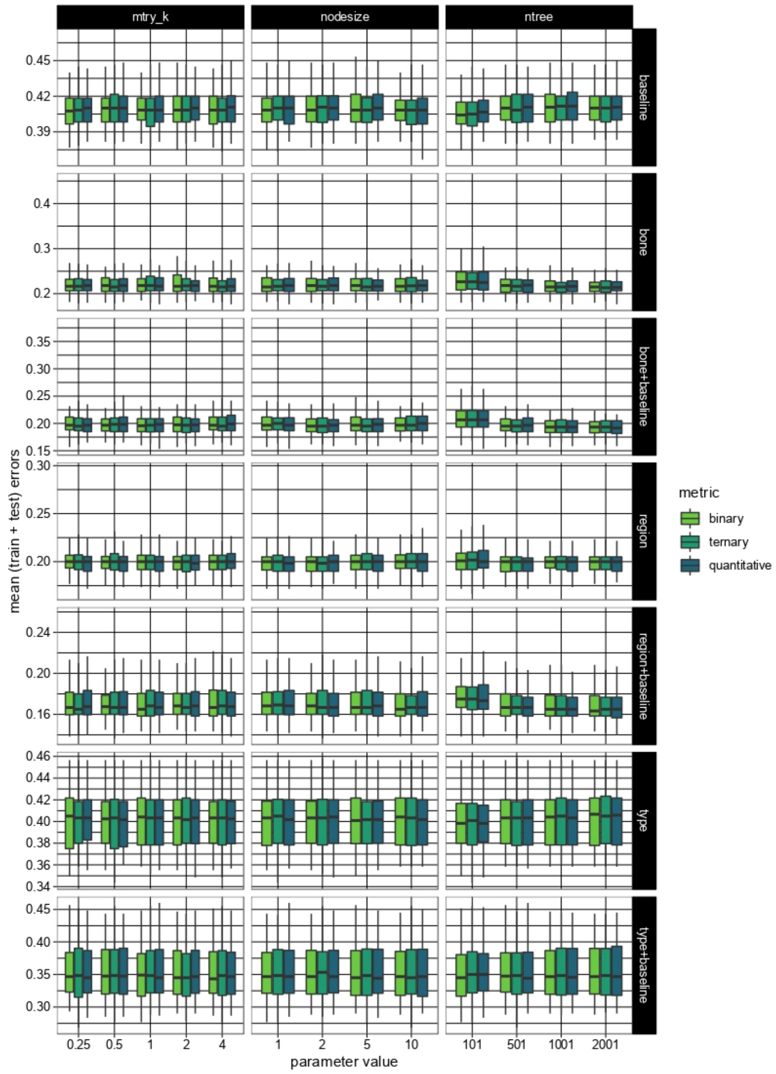

Figure 1. Random forest parameter optimization of all the models.

3.3. Benchmarking Models

Various models were tested using the parameters selected above (Figure 2).

The error of the models based on the type of fractures or only with baseline was 35% or greater.

The best models were inferior to 25% and were based on the bone or the region of fractures, with or without the baseline. Thus, for the next step, we omitted the type of fractures.

The results were similar for the three rating systems (binary, ternary, and quantitative). We decided to keep the binary quotation because it showed very few inter- and intra-observer errors.

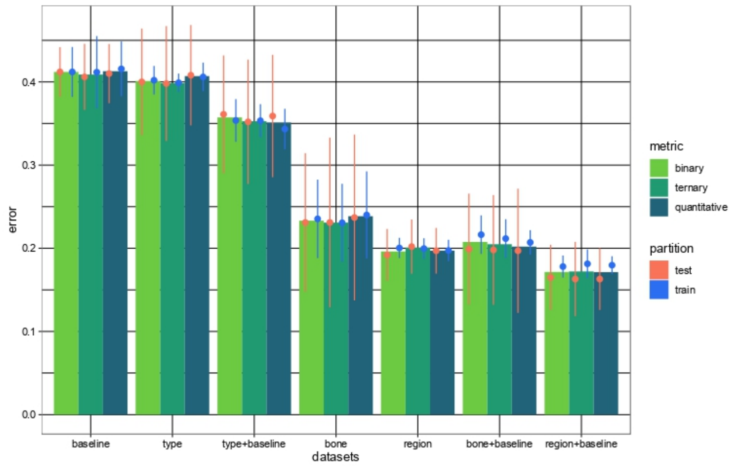

Figure 2. Error rates of all the models in test and train samples by random forest.

3.4. Exploring Class-Wise Predictions for the Final Four Models

The results of the final four models, bone, bone and baseline, region of fracture, and region of fracture and baseline, are presented in Figure 3.

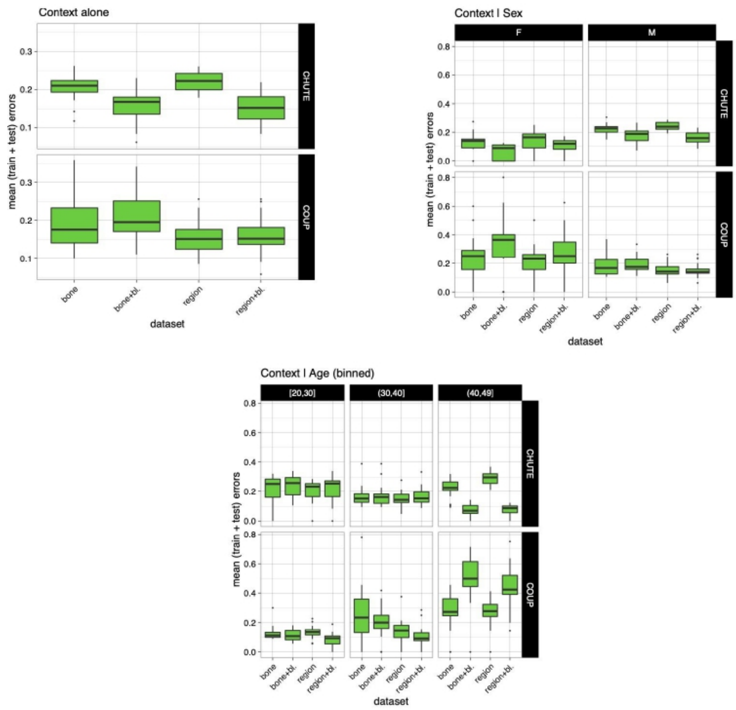

Figure 3. The error rate of the models was based on fractures in the anatomical regions and bone with or without baseline by etiology, sex, and age.

The second part of the figure shows the relationship between context and sex. The rate error in falls for females varied between 0% and 20%; for males, it was between 14% and 28%. For blows, the rate error varied for females between 17% and 40%; for males, it was between 12% and 23%.

The third part of the figure shows the relationship between context and age. The rate error in falls for individuals aged between 20 and 29 years was 17% to 30%; for individuals aged between 30 and 39 years old it was 12% to 20%; and for individuals aged between 40 and 49 years old, it was 10% to 32%. The rate error in blows for individuals aged between 20 and 29 years old was 7% to 15%; for individuals aged between 30 and 39 years old it was 9% to 37%; and for individuals aged between 40 and 49 years old, it was 25% to 61%.

3.5. Variable Importance in Model

The variable importance of the final four models, bone, bone and baseline, region of fracture, and region of fracture and baseline, are presented in Figure 4.

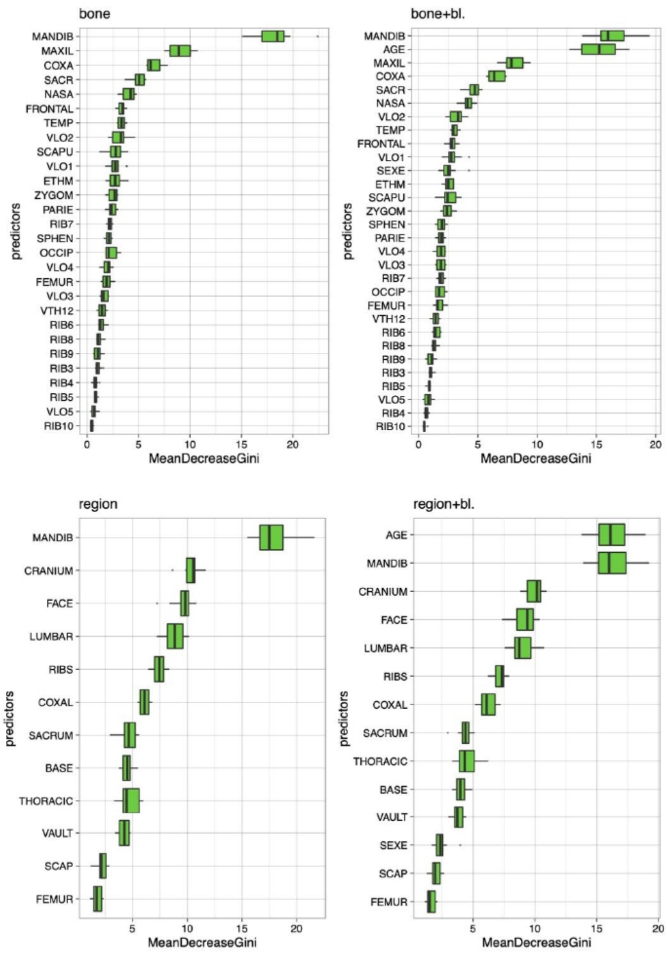

Figure 4. Variable importance for the four final models based on fractures in the anatomical regions and bones with or without baseline.

The most important predictors in the model based on bone were fractures in the mandible, maxilla, coxal, sacrum, and nasal bone.

The most important predictors in the model based on bone and baseline were fractures in the mandible, the individual's age, and fractures in the maxilla bone, coxal bone, and sacrum.

The most important predictors in the model based on the anatomical region were fractures in the mandible, cranium, face, lumbar, and ribs.

The most important predictors in the model based on the anatomical region and baseline were the individual's age and fractures in the mandible, cranium, face, and lumbar.

Fractures in the cranium, mandible on the pelvic girdle, lumbar, and ribs were very important in the distinction between falls and blows.

Notably, the two most essential parameters in these four models were the mandible and the patient's age.

To observe which localization of fracture tended to be more caused by blows or falls, we created Figure 5.

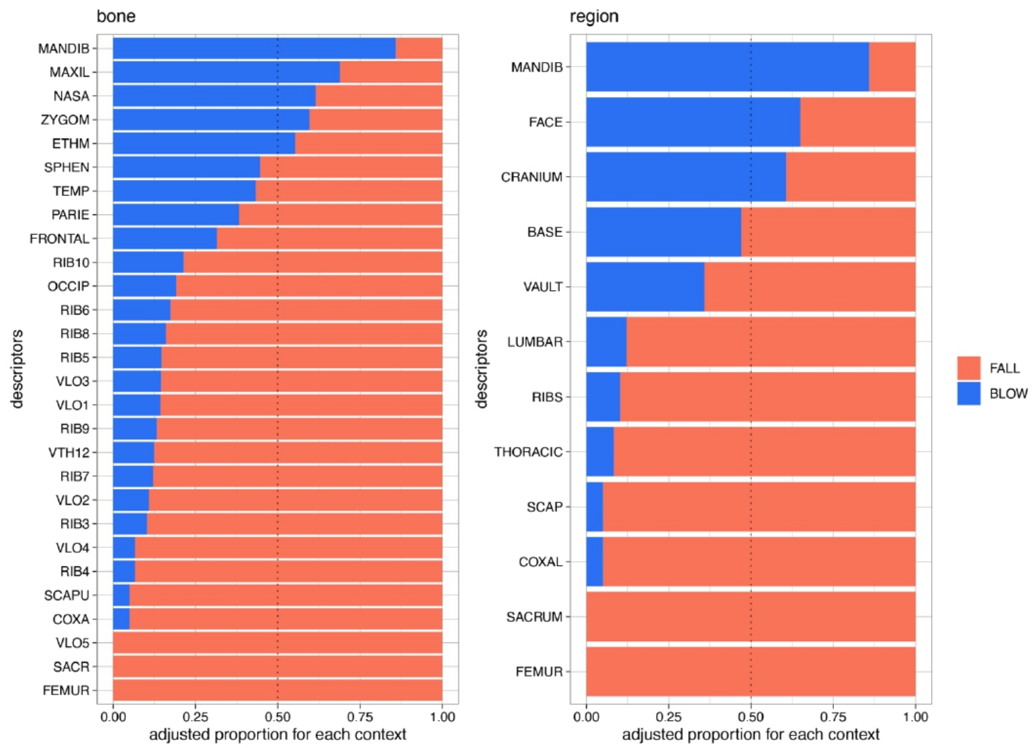

Figure 5. Distribution of the fractures in the anatomical region and bones according to the etiology.

This figure shows the distribution of the most relevant parameters in the distinction between falls and blows.

The left shows the fractures in bones. Fractures in the mandible, maxillary, nasal, zygomatic, and ethmoid bones are more frequent due to blows than falls. No fractures of the fifth lumbar vertebrae, sacrum, and femur were observed in blow cases. The other fractures were more present in fall cases than in blow cases.

The right side of Figure 5 shows the classification of fractures present in the anatomical regions. Fractures in the mandible, face, and cranium were more frequently observed as a result of blows than falls. No fractures in the sacrum and femur were observed in blow cases. Fractures in the basicranium, vault, lumbar vertebrae, ribs, thoracic vertebrae, scapula, and coxal bone were more frequent in fall cases than in blows.

4. Discussion

4.1. Repeatability

The results presented a substantial to perfect agreement for most of the variables, especially in the case of binary quotation.

4.2. Fracture Location, Sex, and Age

Figure 3 shows differences between the rate of error between males and females and between the age classes in blow cases. The error rate was important for females and individuals aged between 40 and 49 years old.

These differences could be explained by the fact that the context of fractures in medical reports may be misinformed or because of the bone's quality. Bone can be weakened by pregnancy or lactation, or in postmenopausal females, among other things [16–19]. This fragility would be more conducive to fractures.

4.3. Model of Prediction

Random forests enabled us to construct models optimized on the observed data, determining new classification criteria. The best prediction models were based on a binary quotation of fractures in 12 anatomical regions or 28 bones with or without baseline (age and sex). These models enabled correct predictions between 77% and 83%.

Fractures in the basicranium, vault, lumbar vertebrae, ribs, thoracic vertebrae, scapula, and coxal bone were more common in fall cases than in blows. These results are concordant with those of Henriques et al. [4].

We discuss fractures in the basicranium and the cranial vault further because this is a particular subject in distinguishing between blows and falls.

According to the literature, thoracolumbar injuries can result from motor vehicle accidents, falls from a significant height, and direct blows [16,20–26].

Rib fractures are common injuries from sports, direct blows or kicking, falls, high-velocity trauma, and cardiopulmonary resuscitation [27–34].

Pelvic fractures are common in motor vehicle accidents, falls, and sport-related accidents [6,16,35,36].

According to the literature, scapula fractures can result from falls, motor vehicle incidents, or direct blows [6,16,36–38].

In our study, fractures in the mandible, maxillary, nasal, zygomatic, and ethmoid bones are more frequent due to blows than falls. Most of these results are concordant with those of Henriques et al. [4].

This is relevant to the study by Wulkan et al. [39] on interpersonal violence-caused panfacial fractures. As for isolated bone structures, the mandible and the nasal had the highest incidence of fractures. Panfacial fractures involve fractures of the frontal bone, maxilla, zygomatic complex, nasoethmoid-orbital region, sphenoid, and mandible [40]. In our case, frontal and sphenoid bone fractures were more frequent in falls than blows.

According to Laski et al. [41], the most frequent etiology of facial trauma is assault (75%), and mandible fractures occur in 46.7% of cases.

The head and the neck are most commonly affected by violence [42].

When we approach the subject of the distinction between blows and falls based on skull fractures, it is difficult not to think of the hat brim line (HBL) rule created by Walcher in 1931 [43]. This refers to an area of the skull between two lines parallel to the Frankfurt horizontal plane; the superior line passes through the glabella, and the inferior line runs through the external auditory meatus [1].

This rule has often been simplified as fractures resulting from falls are often located within the HBL, whereas fractures resulting from blows may be found above and within the HBL, but not on the skull base [1,2,43–45].

Some studies have shown that it is more complex, even if the idea that fractures above the HBL occur in cases of falls remains recurrent.

Ehrlich and Maxeiner observed that lacerations from blows more often occur above the HBL than from falls [46,47].

Kremer et al. [1,2] showed that injuries from blows are more often found above the HBL; a laceration within the HBL is more in favor of a fall; and a skull fracture within the HBL is found equitably in both etiologies.

The results from Guyomarc'h et al. [44] showed that blows can be distinguished from falls due to four criteria, including fractures above the HBL.

Our results showed that fractures in the vault and the basicranium occurred more frequently in fall cases than in blows. Our previous study demonstrated the same results [4]. This is discordant with the HBL rule.

According to the HBL rule, fractures resulting from blows will not be found on the skull base.

This last point can also be contradicted by the study by Ta'ala et al. (2006); we should focus on the context of trauma, because their research revealed that cranial trauma was more likely caused by execution with a variety of blunt weapons applied to the back of the head/neck by Khmer Rouge soldiers [48]. Moreover, a victim can fall during an assault.

Rogers [49] wrote that fractures in the basicranium could indirectly result from blows to the front of the head or through the compression of the spine against the base of the skull.

Research by Lefèvre et al. (2015), regarding differences in injuries caused by falls from less than 2.5 m high and homicides, the incidence of cranial fractures in both etiologies was similar [50]. In their study, the HBL could have been more helpful in distinguishing between falls and blows.

The difference in the occurrence of fractures between this study and ours can be explained by the different heights of falls. Lefevre et al. (2015) selected low falls; we did not select a height for falls [50]. Greater heights result in a wider distribution and greater severity of fractures than accidental falls [34,37].

Many studies have shown that fractures and injuries on the cranial vault and above the HBL could result from repeated falls, falls from a height, or an impact against an edge or a corner, such as falls involving stairs [1–3,43,43,44,46,47,51].

According to Geserick et al. (2014), the HBL rule does not apply to blows and falls from a height (including from stairs) [3].

The HBL rule suggests that fractures from falls do not lie above the hat brim line when some conditions are fulfilled (i.e., standing position of the individual before falling, flat floor without incline or stairs, falling from one's height, or the absence of intermediate obstacles) [3,43].

These application parameters are often omitted, which could explain the results of studies based on the HBL rule.

Additionally, the HBL rule should be used with caution because studies of the discrimination of falls and blows are based only on fractures in the skull (cranial vault and basicranium).

The localization of fractures in the cranium is not discriminatory of one etiology or another; however, according to our results, the presence of fractures in the fifth lumbar vertebrae, sacrum, and proximal extremity of the femur seems to be for blow cases.

According to the literature, thoracolumbar injuries occur in falls from a significant height [16,20–25]. However, fractures of the lumbar transverse processes may occur due to direct blows to the lumbar area [26].

The research performed by Mullingan and Talmi on 357 cases of assault found two patients with lumbar spine transverse process fractures at the L5 level, but not on the pelvis or the femur [52].

Many researchers have found that femur fractures result from falls from heights [6,16,36,53].

Sacral fractures frequently occur in falls. However, these can also occur due to direct blows [54–59]. Some cases, such as that studied by Berryman and Saul, present cases of violent sexual assault with a fractured sacrum caused by a tire iron inserted vaginally [60].

Our method can be helpful to forensic experts in determining the manner and death and the distinction between homicidal death by blunt trauma and falls.

Moreover, anthropologists and pathologists can testify in courtrooms; evidence presented in court must follow Daubert's guidelines for validity and reliability (evidence validated; the error rates known; standards available; and the findings should be peer-reviewed and accepted by the scientific community) [61,62].

To the best of our knowledge, no method of distinction between falls and blows has been proposed based on a statistically viable sample, with error rates known and strong statistics.

Our results show that it is possible to discuss the etiology when determining the probability of belonging to one etiology or another.

However, notably, this method was based on individuals aged between 20 and 49 years old. Its application and results are not assured for individuals not belonging to the same age group.

Moreover, this method will be tested on a forensic sample; for easy use and response, it will be developed in applications to register fractures.

5. Conclusions

In this study, we investigated fall and blow distinctions using random forest classification. The results indicated a good separation between the two etiologies using binary coding on 12 anatomical regions or 28 bones. Further evaluation of this classification system is needed as validation on forensic subjects with the mode of occurrence of fractures known.

However, these preliminary results support the possibility that this system for distinguishing falls from blows could be a relevant tool for experts, with prediction rates between 77% and 83%.

In future studies, we intend to develop an application to register fractures and give us the probability that these come from one etiology or another.

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Informed Consent Statement: Patient consent was waived so as not to disclose or compromise their identity.

Data Availability Statement: The data for this study are kept by the first author.

Conflicts of Interest: The authors declare no conflict of interest.

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Annex III : Supplementary material table

Table 15: Fracture morphologies recorded

Skeletal Region	Fracture Morphology	Code	Bibliography
Cranial Vault			
Frontal	Linear	F1	Wedel, Galloway 2014, p. 139
	Diastatic	F2	Wedel, Galloway 2014, p. 139
	Depressed	F3	Wedel, Galloway 2014, p. 139
	Radiating	F4	Christensen *et al.*, 2021, p. 11
	Concentric	F5	Christensen *et al.*, 2021, p. 11
	Comminuted	F6	Wedel, Galloway 2014, p. 140
	Mixte (2 types above exluding comminuted)	F7	Henriques, 2023
Parietal	Linear	P1	Wedel, Galloway 2014, p. 139
	Diastatic	P2	Wedel, Galloway 2014, p. 139
	Depressed	P3	Wedel, Galloway 2014, p. 139
	Radiating	P4	Christensen *et al.*, 2021, p. 11
	Concentric	P5	Christensen *et al.*, 2021, p. 11
	Comminuted	P6	Wedel, Galloway 2014, p. 140
	Mixed (2 types above exluding comminuted)	P7	Henriques, 2023
Basicranium			
Occipital	Linear	O1	Wedel, Galloway 2014, p. 139
	Diastatic	O2	Wedel, Galloway 2014, p. 139
	Depressed	O3	Wedel, Galloway 2014, p. 139
	Radiating	O4	Christensen *et al.*, 2021, p. 11
	Concentric	O5	Christensen *et al.*, 2021, p. 11
	Comminuted	O6	Wedel, Galloway 2014, p. 140
	Mixed (2 types above exluding comminuted)	O7	Henriques, 2023
	Occipital Condylar	OCC	Wedel, Galloway 2014, p. 144
	Occipital Ring Fract	OCR	Wedel, Galloway 2014, p. 144
Pars Basilaris	Sagittal	PBO1	Henriques, 2023
	Transversal	PBO2	Henriques, 2023
	Oblique	PBO3	Henriques, 2023
Sphenoid	Linear	S1	Wedel, Galloway 2014, p. 139
	Diastatic	S2	Wedel, Galloway 2014, p. 139
	Depressed	S3	Wedel, Galloway 2014, p. 139
	Radiating	S4	Christensen *et al.*, 2021, p. 11
	Concentric	S5	Christensen *et al.*, 2021, p. 11
	Comminuted	S6	Wedel, Galloway 2014, p. 140
	Mixed (2 types above exluding comminuted)	S7	Henriques, 2023
	Pterygoid process	PPT	Wedel, Galloway 2014, p. 144
	Body	SC	Henriques, 2023
	Small wing	SPHPA	Henriques, 2023
Temporal	Linear	T1	Wedel, Galloway 2014, p. 139
	Diastatic	T2	Wedel, Galloway 2014, p. 139
	Depressed	T3	Wedel, Galloway 2014, p. 139

	Radiating	T4	Christensen *et al.*, 2021, p. 11
	Concentric	T5	Christensen *et al.*, 2021, p. 11
	Comminuted	T6	Wedel, Galloway 2014, p. 140
	Mixed (2 types above exluding comminuted)	T7	Henriques, 2023
	Petrous portion	PP	Wedel, Galloway 2014, p. 143
Zygomatic process	Simple	PZT1	Henriques, 2023
	Comminuted	PZT2	Henriques, 2023
Mastoid portion	Linear	PMT1	Wedel, Galloway 2014, p. 139
	Longitudinal	PMT9	Wedel, Galloway 2014, p. 144
	Transverse	PMT10	Wedel, Galloway 2014, p. 144
	Radiating	PMT11	Christensen *et al.*, 2021, p. 11
Face			
Maxilla	Le Fort I	MA1	Wedel, Galloway 2014, p. 153
	Le Fort II	MA2	Wedel, Galloway 2014, p. 153
	Le Fort III	MA3	Wedel, Galloway 2014, p. 153
	Simple	MA4	Henriques, 2023
	Comminuted	MA5	Henriques, 2023
	Mixte	MA6	Henriques, 2023
Palatine	Sagittal Fracture	PA1	Henriques, 2023
	Transversal Fracture	PA2	Henriques, 2023
	Oblique	PA3	Henriques, 2023
	Comminuted	PA4	Henriques, 2023
	Mixed (2 types above exluding comminuted)	PA5	Henriques, 2023
Vomer		V	Wedel, Galloway 2014, p. 151
Ethmoid		E	Wedel, Galloway 2014, p. 151
Lacrimal		L	Wedel, Galloway 2014, p. 151
Nasal		N	Wedel, Galloway 2014, p. 150
Zygomatic	Isolated fracture of one of the processes	Z1	Wedel, Galloway 2014, p. 147
	Fractures of all three processes (tripod fracture)	Z2	Wedel, Galloway 2014, p. 147-148
	Fracture of two processes	Z3	Henriques, 2023
	Comminuted	Z4	Wedel, Galloway 2014, p. 148
	Mixed (2 types above exluding comminuted)	Z5	Henriques, 2023
Mandible			
Mandible	Ascending ramus/angle fracture/ condylar fracture	MD1	Wedel, Galloway 2014, p. 154
	Symphysis	MD2	Wedel, Galloway 2014, p. 154
	Body	MD3	Wedel, Galloway 2014, p. 154
	Comminuted	MD4	Henriques, 2023
	Mixed (2 types above exluding comminuted)	MD5	Henriques, 2023
Shoulder Girdle			
Clavicle	Lateral extremity/acromial end	CL1	Wedel, Galloway 2014, p. 198
	Medial extremity/sternal end	CL2	Wedel, Galloway 2014, p. 198
	Spiral/oblique	CL3	Marsh *et al.*, 2007, S73
	Transverse	CL4	Marsh *et al.*, 2007, S73

	Comminuted	CL5	Henriques, 2023
	Mixte	CL6	Henriques, 2023
Scapula	Body	SCP1	Marsh *et al.*, 2007, S69-70
	Coracoid	SCP2	Marsh *et al.*, 2007, S69-
	Articular surface	SCP3	Marsh *et al.*, 2007, S69-70
	Spinal	SCP4	Wedel, Galloway 2014, p. 202
	Neck	SCP5	Wedel, Galloway 2014, p. 202
	Comminuted	SCP6	Marsh *et al.*, 2007, S69-70
	Mixed (2 types above exluding comminuted)	SCP7	Henriques, 2023
Thoracic cage			
Ribs	Anterior arch	1	Wedel, Galloway 2014, p. 191
R 1	Middle arch	2	Wedel, Galloway 2014, p. 191
R 2	Posterior arch	3	Wedel, Galloway 2014, p. 191
R 3	Comminuted	4	Henriques, 2023
R 4	Mixed (2 types above exluding comminuted)	5	Henriques, 2023
R 5			
R 6			
R 7			
R 8			
R 9			
R 10			
R 11			
R 12			
Manubrium	Transverse fracture	ST1.1	Wedel, Galloway 2014, p. 194
	Longitudianl fracture	ST1.2	Wedel, Galloway 2014, p. 194
	Oblique/backward angulation	ST1.3	Wedel, Galloway 2014, p. 194
	Mixte	ST1.5	Henriques, 2023
	Comminuted	ST1.6	Henriques, 2023
Body of the sternum	Transverse fracture	STC.1	Wedel, Galloway 2014, p. 194
	Longitudianl fracture	STC.2	Wedel, Galloway 2014, p. 194
	Oblique/backward angulation	STC.3	Wedel, Galloway 2014, p. 194
	Mixed (2 types above exluding comminuted)	STC.5	Henriques, 2023
	Comminuted	STC.6	Henriques, 2023
Hyoid Bone	Horn	H	Wedel, Galloway 2014, p. 159
	Body	HB	Wedel, Galloway 2014, p. 159
Cervical vertebrae			
Atlas	One arch	VC1.1	Wedel, Galloway 2014, p. 169
	Jefferson fracture	VC1.2	Wedel, Galloway 2014, p. 169
	Lateral Mass fracture	VC1.3	Wedel, Galloway 2014, p. 169
	Transvers process fracture	VC1.4	Wedel, Galloway 2014, p. 169
	Comminuted	VC1.5	Henriques, 2023
	Mixed (2 types above exluding comminuted)	VC1.6	Henriques, 2023
Axis	Oblique body	VC2.1	Wedel, Galloway 2014, p. 173

	Transverse process	VC2.2	Wedel, Galloway 2014, p. 173
	Arch	VC2.3	Wedel, Galloway 2014, p. 173
	Odontoid	VC2.4	Wedel, Galloway 2014, p. 171
VC3	Fracture	1	Wedel, Galloway 2014, p. 175
VC4	Compression	2	Wedel, Galloway 2014, p. 175
VC5	Spinous process	3	Wedel, Galloway 2014, p. 175
VC6	Lateral mass fracture	4	Wedel, Galloway 2014, p. 175
VC7	Burts fracture/comminuted	5	Wedel, Galloway 2014, p. 175
	Mixed (2 types above exluding comminuted)	6	Henriques, 2023
Thoracic/Lumbar Vertebrae			
VT1	Fracture of one plate	1	Wedel, Galloway 2014, p. 181
VT2	Compression	2	Wedel, Galloway 2014, p. 179
VT3	Chance fracture	3	Wedel, Galloway 2014, p. 182
VT4	Spinous process	4	Wedel, Galloway 2014, p. 181
VT5	Transverse process	5	Wedel, Galloway 2014, p. 181
VT6	Fracture of both plate/comminuted	6	Wedel, Galloway 2014, p. 181
VT7	Mixed (2 types above exluding comminuted)	7	Henriques, 2023
VT8	Posterior arch	8	Wedel, Galloway 2014, p. 184
VT9			
VT10			
VT11			
VT12			
VL1			
VL2			
VL3			
VL4			
VL5			
Pelvic Girdle			
Sacrum	Transverse	SAC1	Wedel, Galloway 2014, p. 187
	Lateral mass fracture	SAC2	Wedel, Galloway 2014, p. 188
	Juxta-articular/articular	SAC3	Wedel, Galloway 2014, p. 188
	Cleaving	SAC4	Wedel, Galloway 2014, p. 188
	Avulsion	SAC5	Wedel, Galloway 2014, p. 188
	Comminuted	SAC6	Henriques, 2023
	Mixed (2 types above exluding comminuted)	SAC7	Henriques, 2023
Coccyx		VCO	Wedel, Galloway 2014, p. 189
Coxal	Iliac	PG.1C1	Wedel, Galloway 2014, p. 247
	Sacroiliac	PG.1C2	Wedel, Galloway 2014, p. 247
	Acetabular	PG.1C3	Wedel, Galloway 2014, p. 247
	Pubic rami/pubis	PG.1C4	Wedel, Galloway 2014, p. 247
	Ischio rami/ischial	PG.1C5	Wedel, Galloway 2014, p. 247
	comminuted	PG.1C6	Henriques, 2023
	Mixed (2 types above exluding comminuted)	PG.1C7	Henriques, 2023
Acetabulum	posterior wall/column	PGAC1	Wedel, Galloway 2014, p. 256

	anterior wall/column	PGAC2	Wedel, Galloway 2014, p. 256
	transverse/posterior wall and transverse	PGAC3	Wedel, Galloway 2014, p. 256
	T-shaped	PGAC4	Wedel, Galloway 2014, p. 256
	Mixed (2 types above exluding comminuted)	PGAC5	Henriques, 2023
	Comminuted	PGAC6	Henriques, 2023
Femur			
Head Neck	Inferior head	FHNC1	Wedel, Galloway 2014, p. 258
	Superior head	FHNC2	Wedel, Galloway 2014, p. 258
	Adduction	FHNC3	Wedel, Galloway 2014, p. 260
	Abduction	FHNC4	Wedel, Galloway 2014, p. 260
	Basicervial	FHNC5	Wedel, Galloway 2014, p. 260
	Comminuted	FHNC6	Henriques, 2023
	Mixed (2 types above exluding comminuted)	FHNC7	Henriques, 2023
Trochanter	Two-part intertrochanteric	FTC1	Wedel, Galloway 2014, p. 262
	Intertrochanteric with trochanteric detachment	FTC2	Wedel, Galloway 2014, p. 262
	Two-part subtrochanteric	FTC3	Wedel, Galloway 2014, p. 265
	Great trochanter	FTC4	Wedel, Galloway 2014, p. 262
	Comminuted	FTC5	Henriques, 2023
	Mixed (2 types above exluding comminuted)	FTC6	Henriques, 2023

Table 16: Fracture morphologies present in the sample by age, sex and etiology

Fracture	AGE							CONTEXT					SEX				
	20-29		30-39		40-49		p	Falls		Blows		p	Female		Male		p
	n	%	n	%	n	%		n	%	n	%		n	%	n	%	
CL1	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	0	0.00	1	0.29	1
CL3	2	1.39	0	0.00	1	0.74	0.78	3	1.28	0	0.00	0.27	0	0.00	3	0.88	1
CL5	1	0.69	1	0.83	2	1.47	0.84	4	1.70	0	0.00	0.15	1	1.72	3	0.88	0.47
CL6	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	0	0.00	1	0.29	1
E	15	10.42	19	15.83	9	6.62	0.06	23	9.79	20	12.12	0.51	5	8.62	38	11.11	0.82
F1	9	6.25	3	2.50	7	5.15	0.35	17	7.23	2	1.21	**0.007**	4	6.90	15	4.39	0.5
F2	0	0.00	2	1.67	0	0.00	0.09	1	0.43	1	0.61	1	0	0.00	2	0.58	1
F3	0	0.00	2	1.67	0	0.00	0.09	0	0.00	2	1.21	0.17	0	0.00	2	0.58	1
F4	0	0.00	3	2.50	1	0.74	0.07	1	0.43	3	1.82	0.31	0	0.00	4	1.17	1
F6	6	4.17	2	1.67	2	1.47	0.31	10	4.26	0	0.00	**0.006**	3	5.17	7	2.05	0.16
F7	4	2.78	4	3.33	0	0.00	0.09	5	2.13	3	1.82	1	1	1.72	7	2.05	1
FHNC1	1	0.69	0	0.00	0	0.00	1	1	0.43	0	0.00	1	0	0.00	1	0.29	1
FHNC3	0	0.00	1	0.83	1	0.74	0.54	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1
FHNC5	2	1.39	1	0.83	0	0.00	0.52	3	1.28	0	0.00	0.27	2	3.45	1	0.29	0.06
FHNC6	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	0	0.00	1	0.29	1
FTC1	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	1	1.72	0	0.00	0.15
FTC2	1	0.69	2	1.67	1	0.74	0.69	4	1.70	0	0.00	0.15	1	1.72	3	0.88	0.47
FTC3	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	0	0.00	1	0.29	1
FTC4	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	0	0.00	1	0.29	1
FTC5	4	2.78	3	2.50	1	0.74	0.44	8	3.40	0	0.00	**0.02**	1	1.72	7	2.05	1
FTC6	0	0.00	1	0.83	1	0.74	0.64	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1
L	0	0.00	2	1.67	2	1.47	0.33	4	1.70	0	0.00	0.15	1	1.72	3	0.88	0.47
MA4	24	16.67	12	10.00	14	10.29	0.19	15	6.38	35	21.21	**<0.001**	5	8.62	45	13.16	0.38
MA5	30	20.83	22	18.33	13	9.56	**0.02**	30	12.77	35	21.21	**0.03**	10	17.24	55	16.08	0.85
MD1	9	6.25	10	8.33	6	4.41	0.43	4	1.70	21	12.73	**<0.001**	2	3.45	23	6.73	0.56
MD3	12	8.33	2	1.67	1	0.74	**0.002**	0	0.00	15	9.09	**<0.001**	0	0.00	15	4.39	0.14
MD4	10	6.94	10	8.33	4	2.94	0.15	7	2.98	17	10.30	**0.004**	3	5.17	21	6.14	1
MD5	9	6.25	4	3.33	2	1.47	**0.11**	4	1.70	11	6.67	**0.01**	2	3.45	13	3.80	1
N	22	15.28	21	17.50	25	18.38	0.78	36	15.32	32	19.39	**0.04**	8	13.79	60	17.54	0.57
O1	1	0.69	7	5.83	6	4.41	**0.04**	10	4.26	4	2.42	0.41	5	8.62	9	2.63	**0.04**
O2	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	0	0.00	1	0.29	1
O6	2	1.39	1	0.83	0	0.00	0.52	3	1.28	0	0.00	0.27	0	0.00	3	0.88	1
O7	1	0.69	2	1.67	2	1.47	0.74	5	2.13	0	0.00	0.08	1	1.72	4	1.17	0.55
OCC	2	1.39	3	2.50	4	2.94	0.7	8	3.40	1	0.61	0.09	2	3.45	7	2.05	0.62
P1	5	3.47	4	3.33	5	3.68	1	10	4.26	4	2.42	0.41	4	6.90	10	2.92	0.13
P3	4	2.78	1	0.83	0	0.00	0.11	0	0.00	5	3.03	**0.01**	0	0.00	5	1.46	1
P4	1	0.69	0	0.00	2	1.47	0.65	3	1.28	0	0.00	0.27	0	0.00	3	0.88	1
P6	3	2.08	1	0.83	3	2.21	0.71	6	2.55	1	0.61	0.25	0	0.00	7	2.05	0.6
P7	1	0.69	2	1.67	1	0.74	0.69	4	1.70	0	0.00	0.15	0	0.00	4	1.17	1

PA1	1	0.69	1	0.83	0	0.00	0.75	1	0.43	1	0.61	1	1	1.72	1	0.29	0.27
PA3	2	1.39	1	0.83	0	0.00	0.52	2	0.85	1	0.61	1	0	0.00	3	0.88	1
PBO1	1	0.69	4	3.33	1	0.74	0.25	4	1.70	2	1.21	1	2	3.45	4	1.17	0.21
PBO3	2	1.39	0	0.00	0	0.00	0.33	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1
PG.1C1	1	0.69	2	1.67	1	0.74	0.69	4	1.70	0	0.00	0.15	0	0.00	4	1.17	1
PG.1C3	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	0	0.00	1	0.29	1
PG.1C4	1	0.69	1	0.83	2	1.47	0.84	3	1.28	1	0.61	0.65	1	1.72	3	0.88	0.47
PG.1C5	0	0.00	2	1.67	2	1.47	0.33	4	1.70	0	0.00	0.15	0	0.00	4	1.17	1
PG.1C6	10	6.94	15	12.50	9	6.62	0.18	33	14.04	1	0.61	**<0.001**	11	18.97	23	6.73	**0.005**
PG.1C7	3	2.08	3	2.50	3	2.21	1	9	3.83	0	0.00	**0.01**	2	3.45	7	2.05	0.62
PGAC3	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	0	0.00	1	0.29	1
PGAC4	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	0	0.00	1	0.29	1
PGAC6	2	1.39	0	0.00	1	0.74	0.78	2	0.85	1	0.61	1	0	0.00	3	0.88	1
PMT1	0	0.00	0	0.00	2	1.47	0.2	1	0.43	1	0.61	1	0	0.00	2	0.58	1
PMT10	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	1	1.72	0	0.00	0.15
PMT11	1	0.69	0	0.00	0	0.00	1	1	0.43	0	0.00	1	1	1.72	0	0.00	0.15
PMT9	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	0	0.00	1	0.29	1
PP	7	4.86	5	4.17	8	5.88	0.84	14	5.96	6	3.64	0.36	6	10.34	14	4.09	0.05
PPT	8	5.56	7	5.83	2	1.47	0.12	10	4.26	7	4.24	1	1	1.72	16	4.68	0.49
PZT1	9	6.25	3	2.50	9	6.62	0.27	12	5.11	9	5.45	1	2	3.45	19	5.56	0.75
PZT2	5	3.47	4	3.33	2	1.47	0.55	4	1.70	7	4.24	0.21	1	1.72	10	2.92	1
R1.1	1	0.69	0	0.00	0	0.00	1	1	0.43	0	0.00	1	0	0.00	1	0.29	1
R1.3	1	0.69	2	1.67	3	2.21	0.6	6	2.55	0	0.00	**0.04**	1	1.72	5	1.46	1
R1.4	1	0.69	1	0.83	0	0.00	0.75	2	0.85	0	0.00	0.51	1	1.72	1	0.29	0.27
R1.5	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	0	0.00	1	0.29	1
R10.1	0	0.00	1	0.83	1	0.74	0.54	0	0.00	2	1.21	0.17	0	0.00	2	0.58	1
R10.2	0	0.00	2	1.67	3	2.21	0.23	4	1.70	1	0.61	0.65	1	1.72	4	1.17	0.55
R10.3	1	0.69	4	3.33	10	7.35	**0.01**	14	5.96	1	0.61	**0.006**	0	0.00	15	4.39	0.14
R10.4	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	0	0.00	1	0.29	1
R10.5	0	0.00	1	0.83	1	0.74	0.54	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1
R11.2	0	0.00	1	0.83	2	1.47	0.4	2	0.85	1	0.61	1	1	1.72	2	0.58	0.38
R11.3	0	0.00	3	2.50	9	6.62	**0.002**	11	4.68	1	0.61	**0.02**	0	0.00	12	3.51	0.23
R11.4	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	0	0.00	1	0.29	1
R11.5	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	0	0.00	1	0.29	1
R12.1	1	0.69	0	0.00	1	0.74	1	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1
R12.2	0	0.00	1	0.83	0	0.00	0.3	0	0.00	1	0.61	0.41	0	0.00	1	0.29	1
R12.3	1	0.69	6	5.00	5	3.68	0.08	11	4.68	1	0.61	**0.02**	3	5.17	9	2.63	0.39
R12.5	0	0.00	0	0.00	3	2.21	0.07	3	1.28	0	0.00	0.27	0	0.00	3	0.88	1
R2.1	0	0.00	0	0.00	3	2.21	0.07	3	1.28	0	0.00	0.27	0	0.00	3	0.88	1
R2.2	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	0	0.00	1	0.29	1
R2.3	2	1.39	1	0.83	4	2.94	0.51	7	2.98	0	0.00	**0.04**	0	0.00	7	2.05	0.6
R2.4	0	0.00	0	0.00	1	0.74	0.64	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1

R2.5	1	0.69	1	0.83	4	2.94	0.33	6	2.55	0	0.00	**0.04**	1	1.72	5	1.46	1
R3.1	1	0.69	2	1.67	5	3.68	0.2	7	2.98	1	0.61	0.15	0	0.00	8	2.34	0.61
R3.2	0	0.00	3	2.50	2	1.47	0.17	4	1.70	1	0.61	0.65	1	1.72	4	1.17	0.55
R3.3	4	2.78	2	1.67	2	1.47	0.74	8	3.40	0	0.00	**0.02**	0	0.00	8	2.34	0.61
R3.5	0	0.00	1	0.83	5	3.68	**0.02**	6	2.55	0	0.00	**0.04**	1	1.72	5	1.46	1
R4.1	0	0.00	1	0.83	2	1.47	0.4	3	1.28	0	0.00	0.27	0	0.00	3	0.88	1
R4.2	0	0.00	2	1.67	3	2.21	0.23	5	2.13	0	0.00	0.08	1	1.72	4	1.17	0.55
R4.3	3	2.08	3	2.50	0	0.00	0.17	6	2.55	0	0.00	**0.04**	2	3.45	4	1.17	0.21
R4.5	0	0.00	1	0.83	6	4.41	**0.008**	6	2.55	1	0.61	0.25	0	0.00	7	2.05	0.6
R5.1	0	0.00	2	1.67	5	3.68	**0.04**	5	2.13	2	1.21	0.7	1	1.72	6	1.75	1
R5.2	3	2.08	2	1.67	3	2.21	1	8	3.40	0	0.00	**0.02**	1	1.72	7	2.05	1
R5.3	4	2.78	2	1.67	2	1.47	0.74	8	3.40	0	0.00	**0.02**	2	3.45	6	1.75	0.33
R5.4	0	0.00	0	0.00	2	1.47	0.2	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1
R5.5	0	0.00	1	0.83	2	1.47	0.4	2	0.85	1	0.61	1	0	0.00	3	0.88	1
R6.1	1	0.69	1	0.83	4	2.94	0.33	5	2.13	1	0.61	0.41	1	1.72	5	1.46	1
R6.2	2	1.39	3	2.50	2	1.47	0.8	7	2.98	0	0.00	**0.04**	1	1.72	6	1.75	1
R6.3	6	4.17	1	0.83	3	2.21	0.26	10	4.26	0	0.00	**0.006**	0	0.00	10	2.92	0.37
R6.4	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	0	0.00	1	0.29	1
R6.5	0	0.00	2	1.67	5	3.68	**0.04**	4	1.70	3	1.82	1	0	0.00	7	2.05	0.6
R7.1	0	0.00	2	1.67	6	4.41	**0.02**	8	3.40	0	0.00	**0.02**	2	3.45	6	1.75	0.33
R7.2	2	1.39	4	3.33	6	4.41	0.33	11	4.68	1	0.61	**0.02**	1	1.72	11	3.22	1
R7.3	2	1.39	2	1.67	4	2.94	0.67	8	3.40	0	0.00	**0.02**	3	5.17	5	1.46	0.09
R7.4	1	0.69	1	0.83	1	0.74	1	2	0.85	1	0.61	1	0	0.00	3	0.88	1
R7.5	0	0.00	0	0.00	3	2.21	0.07	2	0.85	1	0.61	1	0	0.00	3	0.88	1
R8.1	1	0.69	1	0.83	2	1.47	0.84	4	1.70	0	0.00	0.15	0	0.00	4	1.17	1
R8.2	1	0.69	4	3.33	3	2.21	0.29	7	2.98	1	0.61	0.15	1	1.72	7	2.05	1
R8.3	3	2.08	4	3.33	9	6.62	0.16	15	6.38	1	0.61	**0.003**	4	6.90	12	3.51	0.27
R8.4	1	0.69	1	0.83	1	0.74	1	2	0.85	1	0.61	1	0	0.00	3	0.88	1
R8.5	0	0.00	1	0.83	2	1.47	0.4	2	0.85	1	0.61	1	0	0.00	3	0.88	1
R9.1	0	0.00	1	0.83	1	0.74	0.54	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1
R9.2	1	0.69	6	5.00	4	2.94	0.08	9	3.83	2	1.21	0.13	1	1.72	10	2.92	1
R9.3	2	1.39	1	0.83	9	6.62	**0.02**	12	5.11	0	0.00	**0.002**	2	3.45	10	2.92	0.69
R9.4	0	0.00	1	0.83	1	0.74	0.54	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1
R9.5	0	0.00	2	1.67	2	1.47	0.33	3	1.28	1	0.61	0.65	0	0.00	4	1.17	1
S1	14	9.72	9	7.50	9	6.62	0.66	21	8.94	11	6.67	0.46	6	10.34	26	7.60	0.44
S2	1	0.69	0	0.00	0	0.00	1	0	0.00	1	0.61	0.41	0	0.00	1	0.29	1
S6	3	2.08	2	1.67	1	0.74	0.69	4	1.70	2	1.21	1	1	1.72	5	1.46	1
S7	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	0	0.00	1	0.29	1
SAC1	2	1.39	0	0.00	3	2.21	0.33	5	2.13	0	0.00	0.08	0	0.00	5	1.46	1
SAC2	2	1.39	1	0.83	2	1.47	1	5	2.13	0	0.00	0.08	1	1.72	4	1.17	0.55
SAC3	5	3.47	5	4.17	2	1.47	0.43	12	5.11	1	0.61	**0.001**	2	3.45	10	2.92	0.69
SAC4	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	1	1.72	0	0.00	0.15
SAC5	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	0	0.00	1	0.29	1
SAC6	6	4.17	10	8.33	10	7.35	0.33	26	11.06	0	0.00	**<0.001**	8	13.79	18	5.26	**0.04**

SAC7	2	1.39	1	0.83	0	0.00	0.52	3	1.28	0	0.00	0.27	1	1.72	2	0.58	0.38
SC	13	9.03	9	7.50	5	3.68	0.18	21	8.94	6	3.64	**0.04**	6	10.34	21	6.14	0.26
SCP1	2	1.39	2	1.67	2	1.47	1	5	2.13	1	0.61	0.41	1	1.72	5	1.46	1
SCP2	0	0.00	2	1.67	0	0.00	0.09	2	0.85	0	0.00	0.51	1	1.72	1	0.29	0.27
SCP3	0	0.00	1	0.83	1	0.74	0.54	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1
SCP4	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	0	0.00	1	0.29	1
SCP5	1	0.69	0	0.00	2	1.47	0.65	3	1.28	0	0.00	0.27	0	0.00	3	0.88	1
SCP6	3	2.08	3	2.50	8	5.88	0.22	14	5.96	0	0.00	**<0.001**	1	1.72	13	3.80	0.7
SPHPA	1	0.69	1	0.83	2	1.47	0.84	4	1.70	0	0.00	0.15	2	3.45	2	0.58	0.1
ST1.2	2	1.39	0	0.00	0	0.00	0.33	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1
ST1.3	0	0.00	1	0.83	1	0.74	0.54	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1
STC1	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	1	1.72	0	0.00	0.15
STC3	2	1.39	1	0.83	4	2.94	0.51	7	2.98	0	0.00	**0.04**	2	3.45	5	1.46	0.27
STC5	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	0	0.00	1	0.29	1
STC6	1	0.69	0	0.00	1	0.74	1	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1
T1	5	3.47	3	2.50	6	4.41	0.7	9	3.83	5	3.03	0.79	1	1.72	13	3.80	0.7
T2	1	0.69	0	0.00	1	0.74	1	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1
T4	4	2.78	2	1.67	1	0.74	0.46	6	2.55	1	0.61	0.25	1	1.72	6	1.75	1
T6	1	0.69	2	1.67	0	0.00	0.3	1	0.43	2	1.21	0.57	0	0.00	3	0.88	1
T7	1	0.69	0	0.00	3	2.21	0.27	4	1.70	0	0.00	0.15	1	1.72	3	0.88	0.47
V	3	2.08	2	1.67	1	0.74	0.69	2	0.85	4	2.42	0.24	0	0.00	6	1.75	0.6
VC1.2	1	0.69	0	0.00	0	0.00	1	1	0.43	0	0.00	1	1	1.72	0	0.00	0.15
VC2.3	0	0.00	1	0.83	1	0.74	0.54	2	0.85	0	0.00	0.51	1	1.72	1	0.29	0.27
VC3.2	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	1	1.72	0	0.00	0.15
VC4.3	1	0.69	1	0.83	0	0.00	0.75	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1
VC4.6	1	0.69	0	0.00	0	0.00	1	1	0.43	0	0.00	1	1	1.72	0	0.00	0.15
VC5.2	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	1	1.72	0	0.00	0.15
VC5.4	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VC5.3	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VC6.2	1	0.69	0	0.00	0	0.00	1	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VC6.5	1	0.69	0	0.00	2	1.47	0.65	3	1.28	0	0.00	0.27	1	1.72	2	0.58	0.38
VC6.3	2	1.39	0	0.00	1	0.74	0.78	3	1.28	0	0.00	0.27	1	1.72	2	0.58	0.38
VC7.1	1	0.69	1	0.83	0	0.00	0.75	2	0.85	0	0.00	0.51	1	1.72	1	0.29	0.27
VC7.3	2	1.39	2	1.67	3	2.21	0.9	7	2.98	0	0.00	**0.045**	1	1.72	6	1.75	1
VC7.5	1	0.69	1	0.83	0	0.00	0.75	2	0.85	0	0.00	0.51	1	1.72	1	0.29	0.27
VCO	2	1.39	2	1.67	2	1.47	1	6	2.55	0	0.00	**0.04**	1	1.72	5	1.46	1
VL1.1	3	2.08	3	2.50	4	2.94	0.92	10	4.26	0	0.00	**0.006**	1	1.72	9	2.63	1
VL1.2	5	3.47	3	2.50	4	2.94	0.94	11	4.68	1	0.61	**0.02**	4	6.90	8	2.34	0.08
VL1.3	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VL1.4	0	0.00	0	0.00	3	2.21	0.07	2	0.85	1	0.61	1	0	0.00	3	0.88	1
VL1.6	1	0.69	2	1.67	4	2.94	0.35	6	2.55	1	0.61	0.25	3	5.17	4	1.17	0.07
VL1.7	2	1.39	1	0.83	7	5.15	0.08	10	4.26	0	0.00	**0.006**	5	8.62	5	1.46	**0.008**
VL1.5	8	5.56	7	5.83	15	11.03	0.18	27	11.49	3	1.82	**<0.001**	6	10.34	24	7.02	0.42
VL1.8	0	0.00	1	0.83	1	0.74	0.54	2	0.85	0	0.00	0.51	1	1.72	1	0.29	0.27

VL2.1	1	0.69	3	2.50	3	2.21	0.4	6	2.55	1	0.61	0.25	1	1.72	6	1.75	1
VL2.2	1	0.69	2	1.67	5	3.68	0.2	8	3.40	0	0.00	**0.02**	2	3.45	6	1.75	0.33
VL2.4	0	0.00	1	0.83	2	1.47	0.4	3	1.28	0	0.00	0.27	0	0.00	3	0.88	1
VL2.6	1	0.69	0	0.00	2	1.47	0.65	3	1.28	0	0.00	0.27	1	1.72	2	0.58	0.38
VL2.5	9	6.25	9	7.50	19	13.97	0.07	34	14.47	3	1.82	**<0.001**	6	10.34	31	9.06	0.81
VL2.7	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VL2.8	1	0.69	0	0.00	0	0.00	1	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VL3.1	0	0.00	1	0.83	1	0.74	0.54	1	0.43	1	0.61	1	0	0.00	2	0.58	1
VL3.2	1	0.69	2	1.67	1	0.74	0.69	4	1.70	0	0.00	0.15	1	1.72	3	0.88	0.47
VL3.4	0	0.00	1	0.83	1	0.74	0.54	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1
VL3.6	1	0.69	0	0.00	2	1.47	0.65	3	1.28	0	0.00	0.27	2	3.45	1	0.29	0.06
VL3.7	0	0.00	1	0.83	1	0.74	0.54	1	0.43	1	0.61	1	0	0.00	2	0.58	1
VL3.5	9	6.25	10	8.33	20	14.71	0.052	35	14.89	4	2.42	**<0.001**	6	10.34	33	9.65	0.81
VL4.1	0	0.00	2	1.67	1	0.74	0.2	2	0.85	1	0.61	1	1	1.72	2	0.58	0.38
VL4.2	1	0.69	1	0.83	4	2.94	0.33	6	2.55	0	0.00	**0.04**	2	3.45	4	1.17	0.21
VL4.4	0	0.00	2	1.67	0	0.00	0.09	2	0.85	0	0.00	0.51	1	1.72	1	0.29	0.27
VL4.6	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VL4.7	1	0.69	0	0.00	1	0.74	1	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1
VL4.5	7	4.86	11	9.17	14	10.29	0.2	30	12.77	2	1.21	**<0.001**	7	12.07	25	7.31	0.29
VL4.8	1	0.69	0	0.00	0	0.00	1	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VL5.1	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VL5.2	1	0.69	1	0.83	1	0.74	1	3	1.28	0	0.00	0.27	0	0.00	3	0.88	1
VL5.4	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VL5.5	6	4.17	6	5.00	5	3.68	0.91	17	7.23	0	0.00	**<0.001**	3	5.17	14	4.09	0.72
VT1.2	0	0.00	2	1.67	0	0.00	0.09	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1
VT1.4	1	0.69	0	0.00	1	0.74	1	2	0.85	0	0.00	0.51	1	1.72	1	0.29	0.27
VT10.1	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	1	1.72	0	0.00	0.15
VT10.2	1	0.69	0	0.00	0	0.00	1	0	0.00	1	0.61	0.41	1	1.72	0	0.00	0.15
VT10.4	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VT10.7	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	1	1.72	0	0.00	0.15
VT10.5	0	0.00	0	0.00	2	1.47	0.2	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1
VT11.1	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	1	1.72	0	0.00	0.15
VT11.2	2	1.39	2	1.67	3	2.21	0.9	7	2.98	0	0.00	**0.04**	1	1.72	6	1.75	1
VT11.4	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VT11.5	2	1.39	0	0.00	4	2.94	0.19	6	2.55	0	0.00	**0.04**	0	0.00	6	1.75	0.6
VT12.1	0	0.00	2	1.67	0	0.00	0.09	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1
VT12.2	3	2.08	0	0.00	1	0.74	0.4	3	1.28	1	0.61	0.65	1	1.72	3	0.88	0.47
VT12.4	0	0.00	1	0.83	3	2.21	0.16	4	1.70	0	0.00	0.15	1	1.72	3	0.88	0.47
VT12.5	0	0.00	1	0.83	5	3.68	**0.02**	6	2.55	0	0.00	**0.045**	1	1.72	5	1.46	1
VT12.6	2	1.39	0	0.00	1	0.74	0.78	3	1.28	0	0.00	0.27	0	0.00	3	0.88	1
VT12.7	1	0.69	2	1.67	1	0.74	0.69	3	1.28	1	0.61	0.65	2	3.45	2	0.58	0.1
VT1.5	2	1.39	1	0.83	1	0.74	1	4	1.70	0	0.00	0.15	1	1.72	3	0.88	0.47
VT2.2	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VT2.4	1	0.69	0	0.00	1	0.74	1	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1

VT2.5	2	1.39	1	0.83	1	0.74	1	4	1.70	0	0.00	0.15	1	1.72	3	0.88	0.47
VT3.1	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VT3.2	1	0.69	0	0.00	0	0.00	1	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VT3.4	1	0.69	0	0.00	2	1.47	0.65	3	1.28	0	0.00	0.27	1	1.72	2	0.58	0.38
VT3.5	1	0.69	0	0.00	0	0.00	1	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VT4.2	1	0.69	0	0.00	0	0.00	1	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VT4.5	1	0.69	0	0.00	0	0.00	1	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VT5.1	1	0.69	0	0.00	0	0.00	1	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VT5.2	1	0.69	0	0.00	0	0.00	1	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VT5.7	1	0.69	1	0.83	2	1.47	0.84	4	1.70	0	0.00	0.15	1	1.72	3	0.88	0.47
VT5.5	1	0.69	0	0.00	0	0.00	1	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VT6.1	2	1.39	1	0.83	0	0.00	0.52	3	1.28	0	0.00	0.27	1	1.72	2	0.58	0.38
VT6.2	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	1	1.72	0	0.00	0.15
VT6.4	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VT6.6	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VT6.5	3	2.08	1	0.83	1	0.74	0.63	5	2.13	0	0.00	0.08	1	1.72	4	1.17	0.55
VT7.2	2	1.39	1	0.83	0	0.00	0.52	3	1.28	0	0.00	0.27	1	1.72	2	0.58	0.38
VT7.6	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	1	1.72	0	0.00	0.15
VT7.7	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	0	0.00	1	0.29	1
VT7.5	1	0.69	0	0.00	2	1.47	0.65	3	1.28	0	0.00	0.27	1	1.72	2	0.58	0.38
VT8.1	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	1	1.72	0	0.00	0.15
VT8.6	0	0.00	0	0.00	1	0.74	0.64	1	0.43	0	0.00	1	1	1.72	0	0.00	0.15
VT8.7	1	0.69	0	0.00	2	1.47	0.65	3	1.28	0	0.00	0.27	0	0.00	3	0.88	1
VT8.5	1	0.69	0	0.00	1	0.74	1	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1
VT9.1	0	0.00	1	0.83	0	0.00	0.3	1	0.43	0	0.00	1	1	1.72	0	0.00	0.15
VT9.2	2	1.39	0	0.00	0	0.00	0.33	2	0.85	0	0.00	0.51	0	0.00	2	0.58	1
VT9.4	1	0.69	1	0.83	1	0.74	1	2	0.85	1	0.61	1	2	3.45	1	0.29	0.06
VT9.5	1	0.69	1	0.83	2	1.47	0.84	4	1.70	0	0.00	0.15	1	1.72	3	0.88	0.47
Z1	5	3.47	5	4.17	6	4.41	0.95	9	3.83	7	4.24	1	4	6.90	12	3.51	0.27
Z2	6	4.17	5	4.17	2	1.47	0.33	5	2.13	8	4.85	0.16	0	0.00	13	3.80	0.23
Z3	7	4.86	1	0.83	8	5.88	0.07	8	3.40	8	4.85	0.61	4	6.90	12	3.51	0.27
Z4	4	2.78	3	2.50	2	1.47	0.77	4	1.70	5	3.03	0.5	2	3.45	7	2.05	0.62
Z5	2	1.39	1	0.83	0	0.00	0.52	2	0.85	1	0.61	1	0	0.00	3	0.88	1