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Generation and Validation of Osseous Fracture Patterns by Forensic Analysis

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ABSTRACT This article presents a method for the generation of bone fracture patterns and their automatic validation through the use of forensic analysis. A tool has been designed that allows the generation of a fracture pattern interactively and guided by the system, based on the study of real cases of fractures. This tool assists the specialist in obtaining fracture patterns according to certain rules taken from the statistical analysis of real cases. Additionally, a parametric fracture pattern generator has been developed. This autonomous generator is able to obtain fracture patterns according to forensic case studies. Once a fracture pattern has been generated, by using one of these two methods the system also provides the validation of this pattern based on a forensic analysis, indicating the feasibility of the fracture pattern being valid and explaining the causes of its validity or non-validity. In addition, these tools provide an analysis not only of the probability of a pattern being correct, but also whether it is capable of detecting some limit patterns that could be valid if experts indicate this circumstance. The system is not closed to new cases, it being possible to include new forensic analysis. Both the interactive tool and the automatic generator, have been validated by experts. The automatic generator tool has been checked for feasibility with forensic statistical analysis. Finally, a usability study was carried out to assess the intuitive use of the interactive tool.

INDEX TERMS Automatic systems, bone fracture, forensic analysis, fracture pattern, generation tools, traumatology, usability, validation tools.

I. INTRODUCTION

A fracture pattern is a representation of the fracture zone of a bone. Normally fracture patterns are extracted from medical images of patients with some trauma. One possible use of the fracture patterns generated in this way is their application to 3D geometric bone models, in order to simulate geometric fractures with a realistic appearance. Generating validated fracture patterns allows us to obtain different types of fractures, including unusual cases and fracture cases that sometimes cannot be observed, in order to create a bone fracture bank. These fractures can serve as input to a simulator or training tool for fracture reduction performed by specialists. Forensic analysis uses the fracture patterns to deduce data about causes and input parameters about an injury.

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In this article, an interactive fracture pattern generator based on forensic analysis is presented. The tool allows the generation of bone fracture patterns according to certain rules. These rules are established through studies of real fractures. Subsequent forensic case analyses can be incorporated to the tool as they occur. This interactive generator also allows the validation of the fracture pattern through a statistical analysis. Therefore it also provides information about valid or invalid fracture patterns. In addition, it would also be possible to use it to guide specialists in the generation of fractures for their application on geometric models in the future. This tool is open to new rules and analysis from data obtained from new forensic analysis of real bone fractures.

The previously described tool allows us to create a fracture pattern. A parametric fracture pattern generator that automatically obtains new patterns accordingly with the rules established by forensic analysis has also been developed. The fracture pattern has been parameterized, obtaining an

algorithm that provides different types of fractures according to a set of custom parameters. As in the case of the interactive tool, this algorithm allows us to incorporate new rules and accommodate new scenarios or restrictions.

The research involved and the development of the tools proposed are essential for the creation and replication of fracture patterns, allowing us to analyze fracture patterns without expensive preparations or experimentation with real bones using force or other treatments. The modification of existing patterns and the recreation of fracture patterns are possible through the characteristics that affect the fracture.

Validation criteria are essential to the interactive or parametric generation of fracture patterns. The principal features of a fracture pattern are analyzed by means of a forensic perspective, based on the study of real casuistics. This allows us to determine whether a fracture pattern is correct or if it could be correct, because some criteria could allow some types of fractures with a degree of certainty. Additionally, a validation by experts has been realized. It allows us to prove that the fracture patterns generated are not only realistic but also correct.

The main contribution of this work is the development of an interactive tool for the generation of fracture patterns, which guides the user in obtaining correct fracture patterns, based on forensic analysis. A parametric tool for this aim is also developed. Both tools allow the validation of the patterns obtained, justifying the decision about their correctness. The results obtained by both tools have been validated not only with an automatic validation based on forensic analysis but also by experts. Limit situations or cases can be obtained and validated in this form, uncommon cases that are difficult to encounter but which are plausible. This validation leads us to obtain a realistic and robust set of fracture patterns, as well as a tool to aid experts in their testing.

The structure of this article is as follows: First, a study of previous work is carried out about the use of fracture patterns in simulations, as well as the obtainment of fracture zones on bone, highlighting the existing tools for the design or representation of bone fractures. This is followed by the forensic studies on which the generation and validation of fracture patterns are based. A characterization of a fracture pattern is also shown. Next, in the material and methods section, the criteria used for both the generation of fracture patterns and their automatic validation outlined. A description is given of the interactive and the parametric tools for the generation of fracture patterns, describing the parameters that govern the fracture patterns from the forensic point of view and the algorithm for the parametric generation. The results section first shows examples of fracture patterns generated with the interactive and parametric tools in order to explain further and in more depth the validation of fracture patterns generated by the proposed tools by using automatic validation and expert judgement. In this form, the tools are validated (interactive and parametric generator, aside from the automatic validation tool), as well as the results obtained with these tools in the form of fracture patterns. This validation is performed and

explained for a selected set of cases, both interactive and parametrically generated, and finally analyzed for a complete set of fracture patterns generated using both methods. A usability study is also performed in this section to assess the intuitive use of the interactive tool. The discussion section analyzes the results obtained and the possibilities of use of these tools, highlighting their advantages and drawbacks. Finally, the conclusions objectively summarize the contributions and future work to be undertaken using these studies and the fracture patterns generated.

II. PREVIOUS WORK

Studies regarding the obtainment of a fracture pattern are based on medical image analysis, but the aim of these studies is totally different to the one proposed here, related to obtaining a valid representation of a fracture pattern based on real cases. Other approaches are based on the generation of fracture patterns for fracturing geometrical models that represent in 3D real or synthetic bones. They use several techniques based on fracture patterns for the simulation of real fractures. On the other hand, some techniques use the fracture zone as a pattern or an approximation for their calculations. This is the case of fracture reduction. Finally, the representation of a fracture pattern used in this and other studies is analyzed, as well as other tools that can be used for the representation or generation of fracture patterns. All these topics are discussed in the following subsections.

A. SIMULATION OF FRACTURES USING FRACTURE PATTERNS

There are a wide range of techniques which use fracture patterns to simulate the fracture of geometric models. Muguercia *et al.* [1] classifies methods for fracture simulation of geometric models into three approaches:

- Based on geometry: this method focuses on the generation of suitable patterns, for the simulation of geometric fractures, obtaining a high degree of control over the fracture in aspects such as the size or shape of the different fragments. The latest advances in this type of fracture suggested by different authors [2]–[4], focus on the decomposition of the model being fractured into different fragments connected through a hierarchy of nodes.
- Based on physics: this approach aims to obtain more realistic fractures through simulation. It is a very complex approach because the mechanical properties of the materials to be fractured need to be identified. Taking into consideration the complexity of this approach, some authors such as Gobron and Chiba [5] propose the use of semi-physical methods to facilitate the study of fracture propagation. The fracture propagation should consider the rules of valid fracture patterns.
- Based on examples: this consists of a set of methods for obtaining a fracture with real appearance, copying the behavior of a natural fracture phenomenon. The

main drawback lies in obtaining real bone fractures. Glondu *et al.* [6] introduce a new method to these types of fractures in which fractures are created in objects by matching certain characteristics of the fracture patterns to objects rather than exactly replicating a fracture.

Although the methods mentioned before are generic to geometric models, they can be applied to bone models after they have been digitized. All the geometric approaches described can use a fracture pattern for guidance in their algorithms or as an example to simulate their fracture processes.

B. DETERMINATION OF FRACTURE ZONE

Another interesting field in which the fracture pattern can be used to possibly validate the determination of the fracture zone is in the automatic reduction of fractures. Most of the time the fractured area is not computed completely, but as an approximation for performing fracture reduction. The analysis of the fracture allows the detection of the cause and the way in which an injury is produced. Therefore, accurate interpretation of a fracture is a fundamental study process today [7]. A complete fracture area determination could help in this topic.

There is a wide range of literature regarding the use of fracture zones for fracture reduction. Below, we focus on studies in which the fracture zone delimitation is significant or could be helped by an accurate fracture pattern.

Some studies [8], [9] perform a selection of points that will act as seeds to automatically expand a region of fracture. Curvature analysis has also been used to identify fractured surfaces. Okada *et al.* [10] present a curvature-based procedure for obtaining fracture lines with the assistance of the user through an interactive process. Curvature detection algorithms have also been applied in order to detect [10] or discard [7] points of interest of the fracture zone.

Other approaches use the shape of the bones to detect the fractured area. Winkelbach *et al.* [11] proposed a method for identifying vertices of the fractured area by comparing its normal relation to the bone axis, Willis *et al.* [12] address the problem with a statistical solution that classifies the points as either belonging to the fracture region or not.

Fürnstahl *et al.* [13] use a normal-based filter to identify points as candidates for belonging to the fracture surface in the proximal humerus, whereby a connected component analysis is applied in order to remove outliers. In [14] an algorithm is proposed for the reconstruction of complex proximal humeral fractures, where the cortical layer is narrow and can be considered a fracture line. Their algorithm is based on the use of curvature scale-space for matching characteristic features between fragments.

Interactive methods have been proposed by authors who have proposed identifying fracture surfaces in craniofacial clinical cases [8], [9]. In these studies, fracture contours are extracted interactively from segmented mandibular fragments. With that aim, specialists must select points belonging

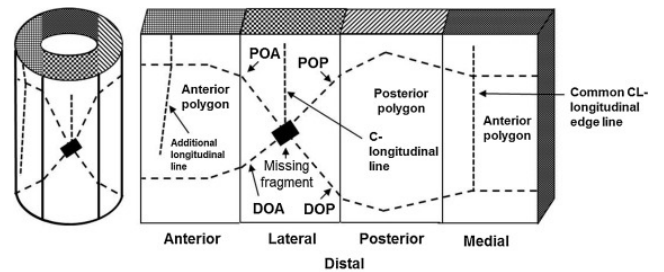


FIGURE 1. Representation of the fracture pattern in 2D in the research conducted by Cohen [22].

to the fractured area and afterwards a contour tracing algorithm generates the rest of the points.

Paulano *et al.* [15] discussed the potential advantages of the generation of fractures on geometric models that represent bone structures in computer-assisted methods that support specialists in fracture reduction interventions.

The combination of the creation or acquisition of valid fracture patterns and the generation of geometric bone fractures with realistic appearance and properties using these fracture patterns [16] can help in processes of virtual training of the fracture reduction process [17]. There is a wide area of interest in the area of computer assisted bone fracture reduction [18] in which the determination of fracture patterns can be of great help.

C. REPRESENTATION OF A FRACTURE PATTERN

A fracture pattern could be represented using spherical coordinates [11], using a 2D texture that includes the whole fractured area [16], or using a 3D representation through a map of heights [19]. Previous representations do not facilitate the entry or generation of new fracture patterns, but rather are representations of actual fracture patterns and as such they schematize or store fractures. Representation using spherical coordinates could be used as a generator of fracture patterns, projected on a 2D plane in a similar manner to the representation used in this article. The fracture patterns found in the literature which use this representation, are formed by a projection on the plane of the four parts into which the bone is usually divided (anterior, posterior, lateral and medial) [20], [21] [22]. This approach to evaluating information facilitates the study of characteristics by specialists, as well as help to form a mental scheme of the fragments generated. The use of this fracture pattern in geometric models to simulate the generation of a real 3D fracture would require the inclusion of additional information about the morphology and physical properties of the bone [15], but this is out of the scope of this article.

The fracture patterns generated are 2D patterns that are similar to the 2D images obtained in forensic articles related to bone fractures. Figure 2 represents the same fracture pattern as the fracture representation obtained from Cohen's study (Fig. 1). Therefore, not only does it enable the representation of new patterns, it also makes it possible to replicate the studies of other experts in the field and validate them.

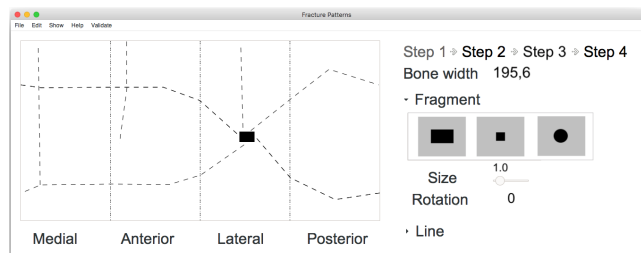


FIGURE 2. Representation of the fracture pattern in the tool developed in this study which is equivalent to the representation proposed by Cohen *et al.* [22].

D. OTHER TOOLS FOR FRACTURE PATTERN GENERATION

Regarding the existing tools for the generation of a fracture pattern using the proposed representation, no tool has been found that enables us to obtain a representation of a fracture pattern in the terms of the representation proposed and used in this study. This is the situation because the drawing editors are not intended for drawing fracture patterns and so are not adapted to them, not being guided, leading to multiple errors. In addition, the importation or exportation of patterns is not possible in a featured mode, which implies that the validation of the fracture is impossible because there is no type of relationship between features or elements.

The tools developed here allow us to obtain valid patterns regarding a starting set of parameters and assumptions based on forensic analysis. They also allow us to validate these patterns in an automatic way, which will make it possible to use them in geometric simulations of fractures for several types of applications such as education or training.

III. FORENSIC ANALYSIS

The aim of the studies related to forensic analysis is to deduce parameters of a certain injury, based on the analysis of the fracture pattern. Thus we can identify the impact direction, the force of the impact, the relative size and shape of the impact body, if there is axial loading in the context of the impact, etc. In this way, we can deduce whether the impact is caused by a pedestrian traffic accident or otherwise, such as standing or running.

The purpose of this study is not the one indicated above, but rather to use the data extracted from the experimentation on bone fracturing to generate a tool that allows us to simulate fracture patterns, as well as to validate the fracture patterns obtained through statistical research. The main parameters that must be taken into account when discerning whether a fracture pattern is valid or not have been identified. The validation is carried out automatically on the generator of the fracture pattern, so that the tool allows us to detect errors in the generation of a fracture pattern.

The tools developed for the generation and validation of bone fractures have been designed a priori using the data extracted from the study of Cohen *et al.* [22] for specific cases of fractures. For the design of the tool the main parameters to take into account have been studied, generating rules that

allow us, on the one hand, to guide the user in the interactive generation of fracture patterns, or to automatically generate fracture patterns following these rules, and on the other hand to take them into account in the automatic validation of the generated fracture patterns generated. These rules can be extended in order to allow the introduction of new forensic studies on fracture patterns, which provide input data and allow the incorporation of rules in the fracture pattern generator and the validation tool.

A. STUDIES ABOUT FRACTURE PATTERNS

Now we have reached this point, we are going to present the results of some studies focused on the deep analysis of the characteristic elements that are involved in the fracturing process through experimentation. The works carried out by experts in the field such as Cohen *et al.* [22] has facilitated the understanding of the relationship between key features in the fracturing process in bone models, such as direction and axial load. This study also reveals that there is a relationship between the complexity of a fracture and the axial load on the bones. Further, they point out that impacts on the lateral and anterior side of the bones produce more fracture lines than impacts on the contralateral side. Bones subjected to axially-loaded impact are significantly more comminuted and fragmented. In addition, the longitudinal line that appears in fractures is longer found in bones subjected to impacts with larger objects, having in most cases a size similar to the impacting body. The size of the impacting body also increases the area of branching and the size of the detached fragment, although if the impact occurs with a round object, no longitudinal line will be created and the oblique lines will be born at the point of impact. There are forensic studies demonstrating that the number, length and curvature of fracture lines created under impact depend on the energy used [20]. Cohen's work also suggests a relationship between velocity and the resulting fracture pattern. There are other aspects that have also been taken into account in other forensic analysis studies [21]. These authors reveal that there is a correlation between the features of a fracture and the geometry of the impact object. In addition, it was also deduced that bones impacted by round objects produce fragments with the form of a false butterfly, but if the impact body is flat and wide, the fragments have the form of a double trapezoid in the area of impact. Another important fact obtained from this study is that the most damaged part is where the impact occurs. Although the studies mentioned above have been carried out on pig bones, the data obtained can be considered representative because the microstructural characteristics of these bones are similar to those of humans [23].

In this article, the results of the research carried out by Cohen *et al.* [22] have been used as a starting point for the generation of specific fracture patterns and validated through the forensic analysis performed. From the data of these results several observations on the morphology of the fractures can be deduced, as well as a set of characteristics that comply statistically with the cases of fractures generated by mechanical

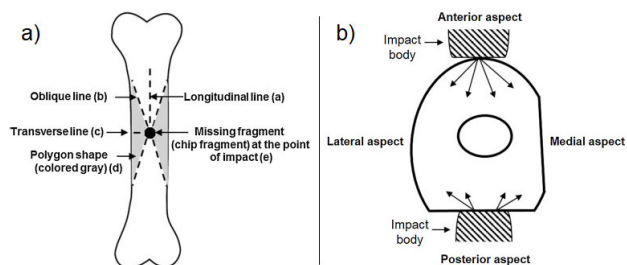


FIGURE 3. Fracture parameters. a) Types of fracture lines in a bone. b) Direction of impact on a bone in 3D [22].

experimentation. There are other studies by the same authors that analyze other experimental characteristics on the forces, geometry of the impact object, speed, etc., as previously mentioned. It is clear that the number of input parameters needed for the generation of a realistic fracture is greater, and that further studies should be conducted to analyze them. The tools developed in this work focus on the factors analyzed by Cohen *et al.* [22], but can be extrapolated to any other study that uses new characteristics of the fracture patterns generated due to a diversity of input parameters. As these studies progress, new features will be incorporated for the generation and validation of fracture patterns that adapt to those studies.

B. CHARACTERIZATION OF A FRACTURE PATTERN

In order to design and incorporate the principal parameters of a fracture pattern, as well as to evaluate the results obtained by the creation of fracture patterns, a study has been carried out using the experimentation of Cohen *et al.* [22].

The experiment carried out by Cohen *et al.* [22] concerns the impact on the diaphysis of long bones, perpendicular to the longitudinal axis, from four different directions (lateral, anterior, medial and posterior), without axial loading, and with impact at a fixed velocity of 3.47m/s . This experiment consisted of four tests, named from Test 1 to Test 4. We deduce a number of variables and rules for the characterization of the fracture pattern based on these experiments.

In their study, a group of measurements related to the studied bones appear, as well as properties observed during the fracturing experimentation. Some of them, such as the “bone length” or the “cross-sectional moment of inertia” are not relevant when determining the characteristics of a fracture.

From the observation of these fractures we can deduce that generally a fracture consists of a possible detachment of a bone fragment in the impact zone, from where oblique fracture lines emerge that propagate laterally towards the remaining aspects of the bone, surrounding them completely most of the time. A common phenomenon is the generation of two fracture lines that completely surround the bone, one in the distal direction and the other in the proximal direction, and which in turn form the so-called fracture polygons. Most of the time, longitudinal lines are also generated. They are usually found in the impact aspect and sometimes in other

aspects, especially in the contralateral aspect. In turn, oblique fracture lines may emerge as ramifications from the fracture lines. In some cases, transverse fracture lines emerge from the impact zone.

Based on the previous observations, we can define some parameters and concepts that will determine the characterization of a fracture pattern:

- **Position (direction) of impact** refers to the direction of the impact (lateral, anterior, medial, posterior).
- **Chip fragment:** missing bone at the point of impact. The basic characteristics studied of the chip fragment are mainly the presence and its diameter length in *mm*.
- **Type of fracture lines:** the types are longitudinal, oblique or transverse lines.
 - **Longitudinal lines** extend proximally or distally parallel to the bone’s longitudinal axis. Longitudinal lines may appear in all aspects of the bone, although they generally appear in the impact area, contralateral face or both. The metric used for this parameter is the presence/absence of longitudinal lines, the number of lines of this type and location.
 - **Oblique lines** extend at an angle to the long axis of the bone. They are generally present extending proximally or distally toward the epiphysis and to other aspects of the bone. The metric used for this parameter is the presence/absence of oblique lines, the number of lines of this type and location.
 - **Transverse lines** are horizontal lines that completely surround the diaphysis, appearing as straight or fractured lines. The metric used for this parameter is the presence/absence of transverse lines.
- **Polygon** is the area between two oblique lines, one in the proximal direction and other in the distal direction from the impact area, usually towards the contralateral aspect. It can be also formed by a transverse and an oblique line.
- **Partial polygon** is the one that is only generated by one fracture line in the proximal or distal direction, generating only part of a complete polygon without being closed.
- **Location of fracture line:** indicates in which aspect of the bone the fracture line is found.
- **Branch line:** oblique line which starts from another fracture line (starts at a branch point).
- **Branch points:** these correspond to the positions along the route of a fracture line from which a line branches out.
- **Shape of the fragment:** this corresponds to the real shape of the chip fragment detached from the bone and can be circular, squared, rectangular, etc.

IV. MATERIALS AND METHODS

The fracture patterns generated by both the interactive tool and the parametric generator must be validated in order to determine whether the fracture patterns obtained are valid or not. There are two methods to validate the patterns obtained.

One of them consists of validation by a group of experts, based on their experience. The second method focuses on obtaining significant characteristics of the patterns and analyzing them based on the statistics obtained by fracturing real bones. We are going to use the second criterion to validate the models obtained automatically, although in the results part we will compare the validation carried out under this parametric system with the judgment of experts, so that the tool used and the criteria used are also validated.

Similarly, the generation of fracture patterns must be guided based on the fulfillment of certain criteria. Having these criteria established a priori will allow us to guide the user in the design of a fracture pattern using the interactive generator and establish an algorithm for the parametric generation of fracture patterns that meet these criteria.

Both the generation and validation of fracture patterns are based on criteria established in the literature. It should be noted that other criteria based on similar studies could be used, and that the tools developed could include these as future studies.

We take as our base the studies of Cohen et. al. [22] and use the statistical values obtained from their analysis as generation and validation criteria. For this, we will carefully review these criteria and how they will be used. Based on these criteria we have designed the tools for the generation of fracture patterns, and finally we have generated a series of cases of fracture patterns, both interactively and automatically, validated in the results section.

A. GENERATION AND VALIDATION CRITERIA

A fracture pattern should fulfill a set of characteristics in order to be valid. When creating a fracture pattern we can guide the user if we know the features that a correct pattern should have. The algorithm for the parametric generation also needs to use these features or criteria in order to obtain valid patterns. Below we describe the criteria used for both, the creation and the validation of fracture patterns, according to the reference study [22].

Once a fracture pattern has been created, it is possible to analyze and validate the fracture pattern generated, according to a set of statistical values obtained from real fractures. Three validation criteria are analyzed and used in this study, as is shown in this section. These criteria focus on counting the number of lines by aspect and their type, length of the fracture lines, the total number of lines, the presence of a fragment and length and distribution of longitudinal lines along the fracture. The method of validation determines whether the fracture pattern falls within the statistics that refer to the different types of pattern in the three validation criteria that have been implemented. In this way, a quantitative comparison is achieved between a specific fracture type and a fracture pattern generated or imported from other systems. So if the fracture pattern passes all the validation criteria, it can be considered correct.

The criteria extracted from the previous article allow a range of values for certain parameters. This does not mean

that a fracture is incorrect if one of the criteria is not strictly met, with a margin of error, but that it could present a more extreme case. Compliance with the set of criteria must be globally assessed.

1) CRITERION 1. ANALYSIS OF THE METRICAL CHARACTERISTICS OF A FRACTURE UNDER DIFFERENT IMPACT DIRECTIONS

For the verification of a fracture pattern it is necessary to analyze the main features referring to several metrics according to the direction of impact:

- Number of fracture lines: this refers to any fracture line larger than 1 centimeter. They may have diverse appearances (longitudinal, oblique, transverse or polygonal).
- Length of the fracture line or the resulting polygon.
- Size of the detached fragment: its presence and size, measured as the circumference length in mm.

Each one of the previous measures in table 1 is checked based on the average and standard deviation, which indicates that it gives us a set of intervals. With this type of parameter we should be cautious, since a greater deviation from the average could indicate a greater number of borderline cases. This must be evaluated globally together with the rest of the measures and validation criteria.

In the case of the number of fracture lines, based on observations made on fractures, there may be cases with values that are far from the average, taking into account the standard deviation.

Concerning the length of the fracture line or the resulting polygon this is not so decisive, as it is also limited or imposed by the size of the diameter of the bone, with a certain variation. This parameter is linked to the number of fracture lines. In the case of a very large or very small number of fracture lines, a value of the length of the fracture line or the polygon will be obtained that makes us think of an invalid fracture pattern.

The size of the detached fragment has a greater range of variation. It is significant that a fragment appears in a fracture pattern when no fragment appears in all the cases studied, clearly indicating that it is an invalid fracture pattern.

In this research we have considered various ranges of acceptance of the parameters that are expressed in the form of average and standard deviation. The first represents most of the cases (68.2%) according to the graph that represents the distribution as the average with an error of one times the standard deviation (Fig. 4). The second represents 27.2% of the cases and corresponds to the interval between one and two times the standard deviation with regard to the average. The third represents an interval of limit cases that represents 4.2% of the cases and corresponds to the interval between two and three times the standard deviation with regard to the average. These intervals lead us to grade the cases globally and determine, for borderline situations, the correctness or not of the fracture patterns. Cases outside these limits have been considered incorrect.

TABLE 1. Statistics concerning to the analysis of the metric characteristics of a fracture according to the direction of impact extracted from Cohen study [22].

Measurements	Direction of impact							
	Lateral		Posterior		Medial		Anterior	
	Mean	± SD	Mean	± SD	Mean	± SD	Mean	± SD
Number of fracture lines	4.5	1.3	2.9	1.7	3.8	1.3	3.6	0.9
Fracture line/polygon length (mm)	265.7	127.7	165.7	92.8	177.8	123.6	176.6	71.5
Chip size (mm)	33.5	13.8	0	0	33.9	16.3	48.9	7.7

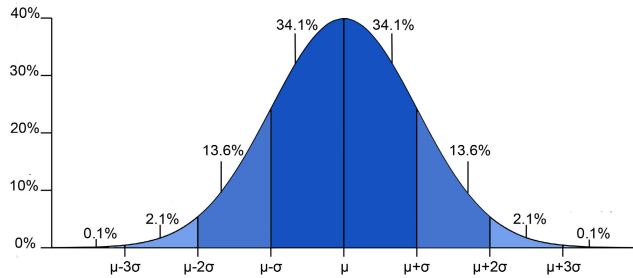


FIGURE 4. Probability distribution around the average in a normal distribution with average μ and deviation σ .

TABLE 2. Statistics concerning the distribution of the location of longitudinal fracture lines according to the direction of impact in the study conducted by Cohen et al. [22].

Impact direction	Location of longitudinal lines (aspects)			
	Impact	Contra lateral	Impact + contra	Anterior
Lateral	25%	50%	0%	25%
Posterior	34%	0%	66%	0%
Medial	57.5%	14%	26.5%	0%
Anterior	72%	14%	14%	0%

2) CRITERION 2. DISTRIBUTION OF THE LOCATION OF LONGITUDINAL LINES ACCORDING TO THE DIRECTION OF IMPACT

This type of validation is based on analyzing the values obtained from a group of real impacts in order to determine which characteristics may not be possible in a given type of fracture (Table 2). For example, in a posterior impact the longitudinal lines should not appear in the contralateral aspect of the bone nor in the anterior aspect.

This criterion determines whether the fracture is incorrect. This test focuses on finding the location of the longitudinal lines, to ensure that they only appear in those aspects that may appear in the statistical results obtained in the study of Cohen et al. [22]. Nevertheless, the criterion shows that the fracture pattern analyzed could be correct, as there are no anomalies in terms of the appearance of longitudinal lines.

3) CRITERION 3. AVERAGE NUMBER OF FRACTURE LINES ACCORDING TO THE DIRECTION OF IMPACT

This criterion analyzes the number of fracture lines in each of the aspects and depends on the impact direction. The method verifies that the values are within the range obtained from the average and the standard deviation. The fracture is considered correct when all the values are within the range (Table 3).

TABLE 3. Statistics on the distribution of the average number of fracture lines according to the direction of impact in the study conducted by Cohen et al. [22].

Impact direction	Bone aspect							
	Lateral		Anterior		Posterior		Medial	
	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
Lateral	4.3	1.2	2.5	0.7	2.2	0.6	2.7	0.9
Anterior	1.8	0.8	4.2	0.8	1.9	0.6	2	0.7
Medial	2.3	0.7	2	0.7	1.3	0.5	2.9	1.5
Posterior	1.4	0.52	2.4	1.1	2	1	1.3	0.5

Here an important consideration is the distribution of fracture lines by aspect taking into account that different values are obtained according to the impact direction.

4) GLOBAL ASSESSMENT

The positive results of the three different criteria indicate that the pattern is correct according to the studies previously mentioned. In the case of a negative result in some criterion it is necessary to perform a global valuation in order to obtain a conclusion about the correctness of the pattern. This is due to isolated cases that can cause a negative result in a criterion. So it is necessary to perform a global assessment of previous criteria.

There are situations in which an incorrect fracture pattern has been generated without doubt, when the number of fracture lines is very large in one aspect in relation to another, or when a fragment appears in a direction of impact in which it has not been observed in previous studies. Thus, a very small or very large number of fracture lines can lead to an incorrect fracture pattern. On the other hand, if it is close to the reference values in borderline case intervals, even if it is not strictly in the range indicated as the majority of cases, it will make us assess other criteria to determine the validity of the fracture.

Some parameters are decisive in obtaining an incorrect fracture pattern and others are not. In these cases, it is necessary to perform an overall evaluation. For example, in relation to the size of the fragment, if it is very small and according to the statistics there should not have been a fragment detachment, we can consider it to be a valid pattern if the rest of the criteria are met. Various similar validations are performed in the results section to indicate how to proceed in certain borderline cases.

It can be considered that in the case of fracture patterns generated automatically by parameters, the fracture patterns comply with the criteria indicated according to the variability established by the percentages, averages and deviations

indicated above. In any case, it is necessary to validate the patterns obtained, both by experts and automatically.

B. GENERATION OF FRACTURE PATTERNS

Several tools have been designed for the generation of fracture patterns based on forensic analysis. The experimentation performed by Cohen *et al.* [22] serves as a basis for considering the parameters which must be used in the generation of a fracture pattern, as well as for the rules for its construction.

Firstly, an interactive tool for the generation of fracture patterns is described. This tool guides the user in the generation of viable fracture patterns, so rules observed in experimentation with fractured bones are used. The drawing of the fracture pattern is manual, but driven by the application.

Secondly, these rules are implemented in an algorithm in which the automatic fracture pattern generation is realized, named the “parametric fracture pattern generator”. Several input parameters are needed for the generation of fracture patterns in a similar way to the ones obtained by experimentation.

In the following subsections the interactive and automatic tools are described.

1) INTERACTIVE FRACTURE PATTERN GENERATION

The main functionalities of the proposed tool consist of the interactive drawing of a fracture pattern for the representation of real fractures. This form of representation allows the delineation of different types of fracture patterns. The user can decide if the pattern will have fragment detachment or not, the shape, size and rotation of the fragment, the number of fracture lines, their type, as well as the position, inclination or branches of the main fracture line or other ramifications. In addition, this editor of fracture patterns allows us to change the thickness of the bone.

As far as the operation of the tool is concerned, it has been simplified regarding other generic tools for drawing, since the user only has to generate the fracture pattern by following a predefined number of steps. Each step implements a set of rules and guides the user with the construction of the fracture. Basically, selecting the type of brush (fragment or line) and its settings, and clicking on the canvas to place these elements. In order to create a fracture pattern using the proposed tool, a set of rules must be taken into account, being advisable previous knowledge related to the generation of fractures, so that it can be carried out properly in a fluent way.

Next, the steps needed for the interactive fracture pattern generation are shown. These steps are followed in the order shown as a guide for the correct generation of the pattern. The steps given can be considered optional since it is not necessary to generate the types of lines and fragments indicated in each step.

1) To choose whether or not the fracture pattern has chip-loss and positioning

When the fracture has a chip detachment or fragment, it will be only necessary to select the shape, orientation

and size of the detached fragment. Then the fragment is situated on the aspect selected for the impact direction on the canvas (Fig. 5a). Otherwise, if the fracture to be generated does not have a fragment, nothing has to be done in this step, just the drawing of the fracture lines starting at a point on the aspect selected for the impact direction. It is possible to select different shapes of the detached fragment (circular, rectangular, squared), as well as to adjust the size, orientation and position of the shape selected when positioned.

The tool considers the position of just one fragment in one aspect of the bone. The maximum size of the fragment is controlled in relation to the dimensions of the aspect on the canvas.

2) Generation of oblique or transverse lines

This step focuses on the drawing of oblique lines which starts from the position of the impact (Fig. 5a). The number of lines of this type is limited in order to draw correct patterns as is indicated in the studies of Cohen. Once this maximum number of lines is reached, the tool gives an alert and asks to go to step three. These lines come out from the fragment and extend with some horizontal inclination. In the case of non existing fragments, lines start at a point selected on the canvas, indicating the position of the impact. Oblique lines could shape polygons when they are connected by longitudinal lines in a next step. Usually one or two oblique lines can surround the bone, starting at the impact position, in a proximal or distal direction. When there are two oblique lines one is distal and the other proximal. Transverse lines are usually generated as horizontal lines which fully encircles the bone.

The tool fixes the starting point of these lines at the fragment or at a point which is used as the position of impact. Then an emerging line is drawn in the direction of another aspect of the bone. The tool gives feedback with guidelines for the transition between aspects, considering the canvas circular (like an expanded cylinder). If the inclination or curvature of the fracture line exceeds a threshold which denotes a wrong fracture, the tool does not allow the line to be drawn. Finally the lines are guided to the position of impact or to the fragment if needed.

3) Generation of longitudinal lines

In this step optional longitudinal lines are drawn (Fig. 5b). The user can choose between drawing this type of line or moving to the next step directly. In this type of fracture lines it is important to know that they can appear either from the detached fragment or the initial fracture point. They can also appear in any part of the non impacted aspects, but only if the longitudinal line intersects with another line. When a longitudinal line appears on the contralateral aspect it usually forms two polygons.

The tool controls the verticality of the line with a given tolerance, as well as the origin and final end of the line

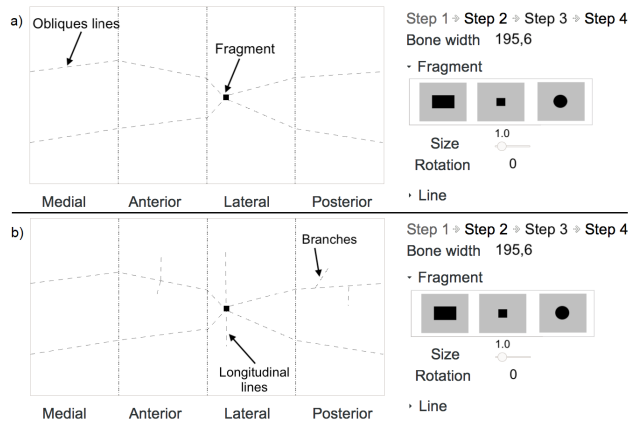


FIGURE 5. a) Completion of the drawing of oblique lines in a fracture pattern and the use of a chip detachment in the fracture editor. b) Longitudinal lines and branches can also be drawn, according to certain rules, in order to represent the fracture pattern.

that should cross oblique or transverse lines or should depart from the fragment or the impact point.

4) Generation of branches

Ramifications of the fracture can be created at this stage. An important factor in the creation of ramifications is to know that they can appear in any type of line except in longitudinal lines. To start a branch it is necessary to select a point (branch point) on an oblique or transverse line and extend to another point on the same aspect.

The tool only allows branches to be generated on oblique or transverse lines. The branch points used as starting points of the branches are enabled only on these types of lines, not allowing other locations. The tool limits the end point to the same aspect in which it starts.

Additionally, traditional methods for editing have also been included in order to facilitate the use of the tool, as well as redo and undo operations. The fracture patterns generated can be saved or exported, in order to visualize them again or import them from another system for their visualization and validation. The characterization of a fracture is stored in a textual form which describes the lines, polygons and fragments, as well as their types, positions, sizes and orientations.

Utilizing this storage format allows us to use the fractures generated, both by the interactive tool and the parametric generation in the validation of the fracture patterns. Similarly, we can import an automatically generated pattern and modify it using the interactive tool.

2) PARAMETRIC (AUTOMATIC) FRACTURE PATTERN GENERATION

An algorithm has been designed for the automatic generation of fracture patterns based on input parameters, which allows us to simulate fracture patterns according to the probabilities and cases studied in the article by Cohen *et al.* [22]. The algorithm allows us to introduce the probability parameters described in that article, to enter other values manually or a combination of both. This will allow the exact use of the data

obtained by the research of Cohen or the incorporation of new data based on other studies.

The input parameters of the algorithm are described below, with a description of them, followed by the algorithm used for the parametric generation.

Parameters

For the generation of features of the fracture pattern, the probability given by Cohen *et al.* [22] should be considered. These probabilities are shown in table 4.

- Impact direction:** it is the direction in which the impact occurs.
ID: Impact direction: $\{L,P,M,A\} = \{Lateral, Posterior, Medial, Anterior\}$
IP(ID): Impact position: (x,y)
- Bone aspect:** it is the position where an element is located, such as a fracture line. It does not have to match the impact direction.
BA: Bone aspect: $\{L,P,M,A\} = \{Lateral, Posterior, Medial, Anterior\}$
Alternatively $\{I,C,I+C,A\} = \{Impact, Contralateral, Impact + Contralateral, Anterior\}$
- Chip Fragment:** to generate the chip fragment, the impact direction is first determined, either randomly or as an input parameter. It refers to fragment detachment. If it occurs, it is located in the same position as the impact direction.
CFP(ID): Chip fragment presence(Impact direction): $\{0-10\}$
CFS(ID): Chip fragment size(Impact direction): $\{real number\}$
CFSSD(ID): Chip fragment size standard deviation(Impact direction): $\{real number\}$
CFA: Chip fragment angle: $\{0-360^\circ\}$
 The presence or not of chip fragment is determined according to table 4 as a function of the impact direction. It is a value between 0 and 10 that expresses the number of cases in which a chip fragment is present out of a total of 10. If it is determined that a chip fragment is generated based on that probability, its size is established based on the size and the size standard deviation parameters of table 1. Finally, it is given an inclination on the vertical based on an angle between 0 and 360°. This parameter can be set and given as input to the algorithm or randomized.
- Polygons:** it refers to the area between two oblique lines.
PP(ID): Presence of Polygons(Impact direction): $\{0-10\}$
 The presence of polygons is determined according to table 4 based on the impact direction. It is a value between 0 and 10 that expresses the number of cases in which there are polygons out of a total of 10. When generating a random number with that probability that a polygon has to be drawn and closed contour fracture lines are generated, allowing us to obtain a polygonal fracture line.
- Fracture lines:** it refers to all the fracture lines created on the fracture.

TABLE 4. Presence of fracture features in different impact directions obtained through the study conducted by Cohen et al. [22].

Measurements	Direction of impact							
	Lateral		Posterior		Medial		Anterior	
	Present	Absent	Present	Absent	Present	Absent	Present	Absent
Longitudinal lines	9	1	3	7	7	3	7	3
Polygon	9	1	4	6	4	6	6	4
Chip fragment	5	5	0	0	3	7	7	3

Bone aspect: $BA = \{L,A,P,M\}$

$FLN(ID,BA)$: Fracture lines number(Impact direction, bone aspect): real number

$FLNSD(ID,BA)$: Fracture lines standard deviation number(Impact direction, bone aspect): real number

The number of fracture lines depends on the impact direction and the bone aspect in which they are located. The number of fracture lines is accompanied by the standard deviation. These data are determined by table 3.

- **Longitudinal lines:** they are lines parallel to the bone longitudinal axis.

Bone aspect: $BA = \{I,C,I+C,A\}$

$LLP(ID)$: Longitudinal lines presence(Impact direction): $\{0-10\}$

$LLPro(ID,BA)$: Longitudinal lines probability(Impact direction, bone aspect): $\{real\ number\}$

The number of longitudinal lines depends on the impact direction and the bone aspect where they occur. Their presence according to the impact direction is determined by a value between 0 and 10 that expresses the number of cases in which there is presence of longitudinal lines out of a total of 10. This number is determined by the data in table 4. The probability of longitudinal lines being produced according to the direction of impact and the bone aspect is determined by table 2.

Algorithm

- 1) Generate impact direction (ID) and impact position (IP(ID)) on the corresponding aspect (BA).
- 2) Generate a fragment in the impact direction:
 - It is determined whether or not there is a fragment in the impact direction according to CFP(ID).
 - If there is a fragment:
 - A random position IP(ID) is calculated on the bone aspect corresponding to the impact direction.
 - A polygonal figure with size according to CFS(ID) and CFSSD(ID) is generated.
 - The fragment is rotated according to the given CFA angle.
- 3) Generation of transverse lines:

It is determined whether or not to generate a transverse line randomly with a probability of 90% and full length surrounding the bone for the medial impact aspect and randomized length for the case of posterior impact.

- 4) Generation of longitudinal lines:

Longitudinal lines of randomized size are generated in the impact and contralateral aspects according to LLP(ID) and LLProb(ID).
- 5) Generation of fracture polygons with oblique lines:
 - It is determined if a complete, partial or non-polygon appears, according to PP(ID), taking into account the presence or not of longitudinal lines generated in the previous step.
 - In the case of a complete or partial polygon with generated contralateral longitudinal line:
 - Oblique lines in the shape of a parabola are generated from the ends of the contralateral longitudinal line generated, ending at the point of impact or the fragment, as appropriate.
 - In the case of a complete polygon, two oblique fracture lines are generated (one proximal and one distal oblique line).
 - In the case of a partial polygon, one fracture line is generated (proximal or distal oblique line).
- 6) Generation of additional longitudinal lines:
 - It is determined whether to generate longitudinal lines in the anterior aspect according to LLP(ID) and LLPro(ID,BA).
 - If this is the case and there are transverse or polygonal lines then a longitudinal line is generated that touches a transverse or polygonal line in the anterior aspect.
- 7) Generation of branch lines:
 - Based on the number of main fracture lines generated previously, the number of branch lines needed to obtain the total number of fracture lines $FLN(ID,BA)$ is determined according to their standard deviation $FLNSD(ID,BA)$ for each aspect.
 - In the aspects where fracture lines are missing, the number of fracture lines necessary to meet the average $FLN(ID,BA)$ and standard deviation $FLNSD(ID,BA)$ are determined.
 - Lines are generated that start from main fracture lines, almost perpendicular to them, randomly and with size relative to both, the length of the fracture line on which it is generated and the position of the branch point.

When a fracture pattern has been automatically generated, as well as in the case of the interactive generation, it is possible to save the fracture or to export it, using the same

format as described previously. In this form it is possible to use in other systems for its visualization and validation.

V. RESULTS

In this section experiments have been carried out related to the generation and validation of the fracture patterns. In a first step, an exhaustive set of fracture patterns was generated by both, the interactive tool and the parametric one. From this set an extracted selection of cases are shown and later discussed in detail. In the next step, experts analyze the cases of fracture patterns generated, expressing their opinion about the validity of the fractures and justifying it. Both types of fractures, interactive and automatically generated fractures, are analyzed. This is followed by an automatic validation as well as a global assessment in which the results obtained with the automatic validation are compared with the expert's validation. Two experts were consulted in the area of traumatology, one radiologist with experience in bone fracture interpretation and a surgeon with wide experience in fracture reduction interventions.

We start with the validation process of a representative set of fracture patterns extracted from the total number of cases. In this form, the process of validation and the conclusions obtained are clarified for specific cases and situations, both for the interactive fracture patterns obtained and the automatic fracture patterns generated. It is followed by an overall study that covers the validation of 64 interactive fracture patterns and 64 parametric fracture patterns, both sets generated by our tools.

Finally, a usability study of the interactive tool was performed, in order to assess its goodness and ease of use.

A. EXTRACTED FRACTURE PATTERN CASES

A selection of fracture patterns both interactively and automatically generated have been extracted in order to analyze and validate in depth. Here we describe first the interactive fracture pattern and then the automatic fracture patterns generated.

1) INTERACTIVE FRACTURE PATTERNS

Here we present a subset of the fracture patterns generated by means of the interactive tool (Fig. 6). The full set has been validated in the same way, but only representative cases are indicated in order to be brief and exhibit some characteristic situations.

- **Interactive Fracture pattern Lateral 1 (IFPL01)**
Represents a fracture with impact on the lateral aspect (Fig. 6a). It has a chip fragment with a rectangular shape and slightly rotated in the lateral aspect of the bone. The pattern has an adequate number of oblique lines, forming two polygons. There are two longitudinal fracture lines, one on the lateral aspect and one on the contralateral aspect. Additional branches appear on the anterior aspect.

- **Interactive Fracture pattern Anterior 2 (IFPA02)**
Represents a fracture with impact on the anterior aspect (Fig. 6b). It has a chip fragment with a large square shape on the anterior aspect of the bone. The pattern has an adequate number of oblique lines, forming two polygons. There are two longitudinal fracture lines, one on the anterior aspect and one on the contralateral aspect. Additional branches do not appear on any aspect.
- **Interactive Fracture pattern Lateral 3 (IFPL03)**
Represents a fracture with impact on the lateral aspect (Fig. 6c). It has a chip fragment with a small square shape on the lateral aspect of the bone. The pattern has two principal oblique fracture lines, forming two polygons, but an additional oblique line extends to the anterior aspect, where additional branches form several polygons; this configuration is not very common in this type of fracture. There is one additional longitudinal fracture line on the contralateral aspect. A branch also appears on the lateral aspect.
- **Interactive Fracture pattern Posterior 4 (IFPP04)**
Represents a fracture with impact on the posterior aspect (Fig. 6d). It has a small chip fragment with a square shape. The pattern has an adequate number of oblique lines, forming two polygons. There is a longitudinal fracture line on the contralateral aspect. There are no branches.
- **Interactive Fracture pattern Anterior 5 (IFPA05)**
Represents a fracture with impact on the anterior aspect (Fig. 6e). It has a small chip fragment with a square shape. The pattern has an adequate number of oblique lines, forming one polygon. There are no longitudinal fracture lines. There are several branches on the impact and contralateral aspects.
- **Interactive Fracture pattern Medial 6 (IFPM06)**
Represents a fracture with impact on the medial aspect (Fig. 6f). It has a small chip fragment with a rotated square shape. The pattern has an oblique and a transverse fracture line, forming two polygons. There are two longitudinal fracture lines, one on the medial aspect and one on the contralateral aspect. There are no branches.

2) PARAMETRIC FRACTURE PATTERNS

Due to the greater variability of cases using the automatic generation of fracture patterns, two valid fracture patterns and one invalid fracture pattern have been selected from each of the four impact aspects of the bone (Fig. 7).

- **Parametric Fracture pattern Anterior 1 (PFPA01)**
Corresponds to the fracture pattern of figure 7a. It has a chip fragment with a rectangular shape. The pattern has an adequate number of oblique lines, forming two polygons. There are two longitudinal lines, one on the contralateral aspect and another one on the chip fragment. There is only a branch on the medial aspect.
- **Parametric Fracture pattern Anterior 2 (PFPA02)**
Corresponds to the fracture pattern of figure 7b. It has a

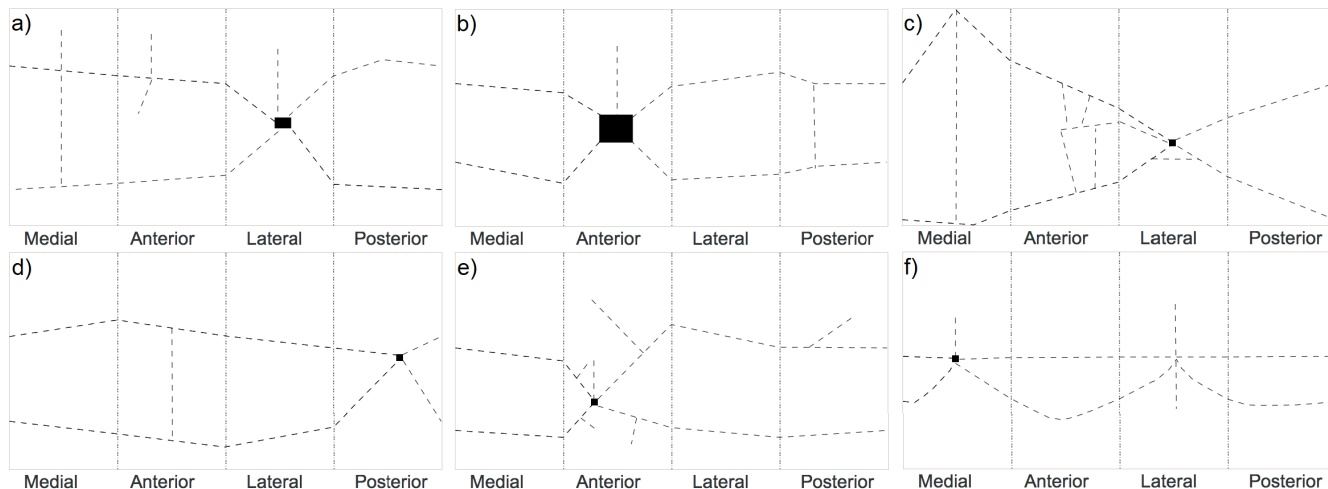


FIGURE 6. This figure represents 6 different cases (a to f) of fracture patterns generated interactively using the tool developed (IFPL01, IFPA02, IFPL03, IFPP04, IFPA05, IFPM06).

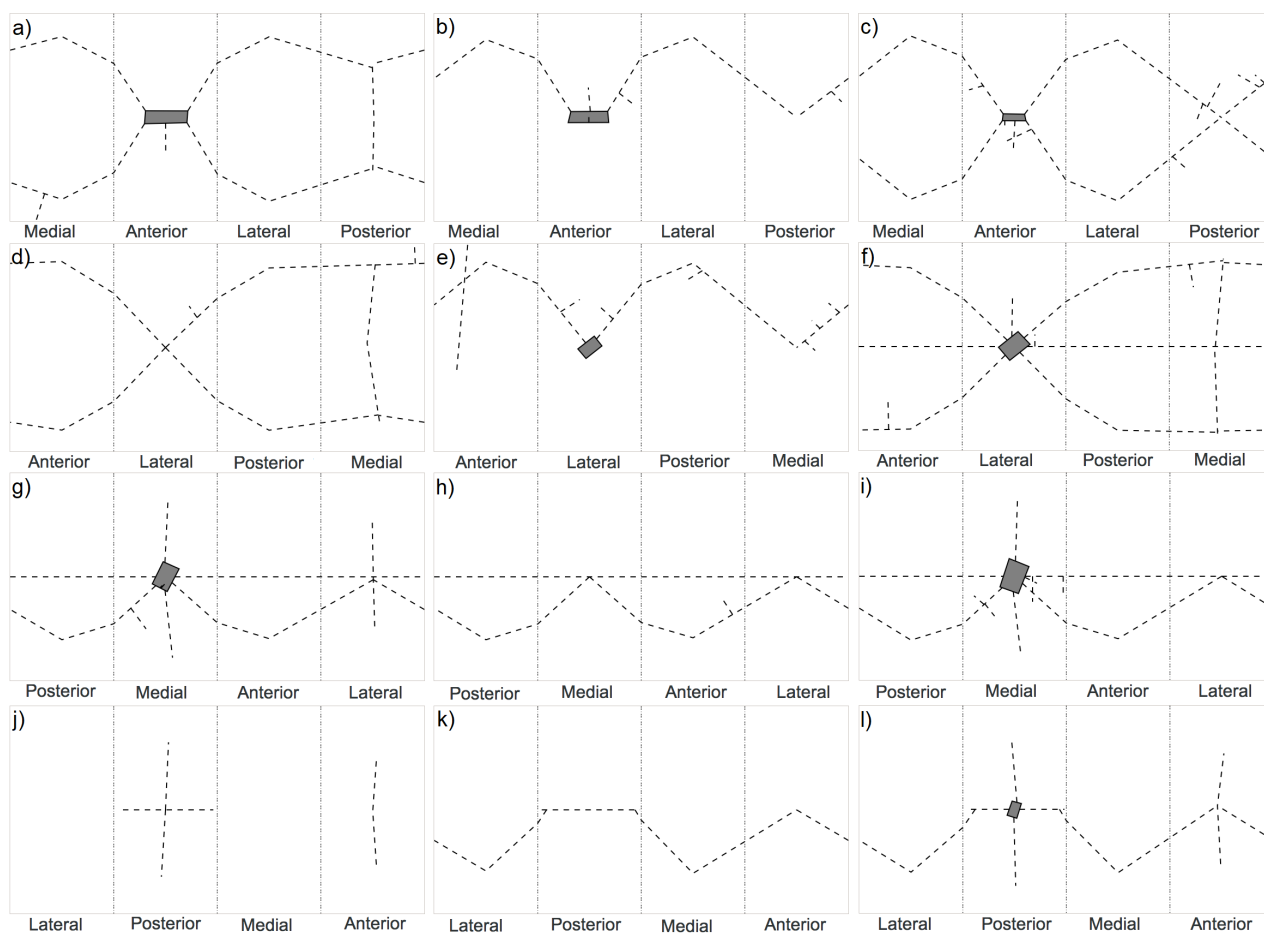


FIGURE 7. Parametric fracture patterns. The first three fracture patterns (PFPA01-03) represent a selected subset of fractures with impact on the anterior aspect (a to c), followed by three (PFPL01-03) for lateral (d to f), (PFPM01-03) medial (g to i) and (PFPP01-03) posterior aspects(j to l). There are two valid and one invalid case for each impact aspect.

chip fragment with a rectangular shape. The pattern has one oblique line, without forming any polygon. There is one longitudinal line, on the chip fragment. There are several branches on the impact and contralateral aspects.

- **Parametric Fracture pattern Anterior 3 (PFPA03)**
Corresponds to the fracture pattern of figure 7c. It has a small chip fragment with a rectangular shape. The pattern has an adequate number of oblique lines, forming

two polygons without longitudinal lines on the contralateral aspect. There is one longitudinal line on the chip fragment. There are several branches on the impact and contralateral aspects.

- **Parametric Fracture pattern Lateral 1 (PFPL01)**
Corresponds to the fracture pattern of figure 7d. It has no chip fragment. The pattern has an adequate number of oblique lines, forming two polygons. There is one longitudinal line, on the contralateral aspect. There are several branches on the impact and contralateral aspects.
- **Parametric Fracture pattern Lateral 2 (PFPL02)**
Corresponds to the fracture pattern of figure 7e. It has a chip fragment with a rotated rectangular shape. The pattern has one oblique line, without forming a polygon. There is one longitudinal line, on the contralateral aspect. There are multiple branches distributed throughout several aspects.
- **Parametric Fracture pattern Lateral 3 (PFPL03)**
Corresponds to the fracture pattern of figure 7f. It has a chip fragment with a rotated rectangular shape. The pattern has an adequate number of oblique lines and also a transverse line, forming four polygons. There are two longitudinal lines, one on the contralateral aspect and another one on the chip fragment. There are branches on the impact and contralateral aspects.
- **Parametric Fracture pattern Medial 1 (PFPM01)**
Corresponds to the fracture pattern of figure 7g. It has a chip fragment with a rotated rectangular shape. An oblique and a transverse line fracture appear, forming two polygons. Longitudinal fracture lines appear on the medial and contralateral aspects. There is only one branch on the medial aspect.
- **Parametric Fracture pattern Medial 2 (PFPM02)**
Corresponds to the fracture pattern of figure 7h. It does not have a chip fragment. An oblique and a transverse line fracture appear, forming two polygons. There are no longitudinal fracture lines but only a branch on the anterior aspect.
- **Parametric Fracture pattern Medial 3 (PFPM03)**
Corresponds to the fracture pattern of figure 7i. It has a chip fragment with a rotated rectangular shape. An oblique and a transverse line fracture appear, forming two polygons. There is a longitudinal fracture line on the medial aspect, and additional branches on this aspect.
- **Parametric Fracture pattern Posterior 1 (PFPP01)**
Corresponds to the fracture pattern of figure 7j. It has no chip fragment, with a transverse fracture line only on the posterior aspect. There are no oblique lines. No polygons appear, nor branches.
- **Parametric Fracture pattern Posterior 2 (PFPP02)**
Corresponds to the fracture pattern of figure 7k. It has not a chip fragment, but a transverse fracture line only on the posterior aspect. Just an oblique line fracture appears, but there are not any polygons. There are no longitudinal fracture lines or branches.

- **Parametric Fracture pattern Posterior 3 (PFPP03)**
Corresponds to the fracture pattern of figure 7l. It has a small chip fragment with a rectangular shape rotated. A transverse fracture line appears on the posterior aspect. Only an oblique line fracture appears, but there are no polygons. There is a longitudinal fracture line on the impact and on the contralateral aspects. There are no branches.

B. VALIDATION OF EXTRACTED CASES

Several experts tested the fracture pattern cases without knowing the result of the automatic validation. The validation of cases was performed independently by each expert. The task of the experts was to verify the validity of the fracture patterns and to explain the reasons that led them to reach their conclusions.

Then the criteria defined for the automatic validation were applied to the fracture patterns, showing the results obtained in a justified form.

Finally, the results obtained after validation by the experts were compared with the results obtained by the automatic validation.

1) VALIDATION OF INTERACTIVE CASES

These cases are more complex because there is no premise about the validity or not of the interactively generated fracture pattern. There are multiple variables and a possible complexity of the pattern due to the ability of the users. For these reasons, the cases studied are described in depth. The values obtained with automatic validation for the interactive fracture patterns can be seen in table 5.

a: Validation of IFPL01

Experts validation

The experts find the pattern correct because it presents a missing fragment in the lateral aspect and its size is adequate for the fracture lines that have been generated. In addition, one of them emphasizes that there are few lines in this type of fracture, so it adapts to the criteria for this type of impact and it is considered correct.

Automatic validation

According to the automatic validation tool, for the criterion 1, in which the characteristics of the fracture are analyzed according to the direction of impact, the three aspects studied are correct: number of fracture lines, length of the fracture lines and size of the fragment. Related to the second criterion, which analyzes the location of longitudinal lines, the result shows that the pattern may have some error because it does not correspond with the statistics, because this criterion indicates that there should not be longitudinal lines in both aspects, impact and contralateral. For a better decision about validation, more criteria should be checked. In the third criterion, the number of fracture lines in each aspect is analyzed, revealing that in all cases the data are within the ranges established in the criterion, classifying the pattern as valid.

TABLE 5. Values obtained with automatic validation for the interactive fracture patterns. Red color indicates values out of range, green color values in the 4.20% interval and blue color values in the 27.20% interval.

Direction of impact	Criterion	Statistics		68.20%		27.20%		4.20%		Case		
		Mean	± SD	Inf	Sup	Inf	Sup	Inf	Sup	IFPA02	IFPA05	
Anterior	1	Number of fracture lines	3.6	0.9	2.70	4.50	1.80	5.40	0.90	6.30	4	8
		Length of fracture lines	176.6	71.5	105.10	248.10	33.60	319.60	-37.90	391.10	156.64	176.73
		Size of fragment	48.9	7.7	41.20	56.60	33.50	64.30	25.80	72.00	123.95	10.29
	2	Location of longitudinal lines									ok	ok
	3	Medial	2	0.7	1.30	2.70	0.60	3.40	-0.10	4.10	2	2
		Anterior	4.2	0.8	3.40	5.00	2.60	5.80	1.80	6.60	3	7
		Lateral	1.8	0.8	1.00	2.60	0.20	3.40	-0.60	4.20	2	2
Posterior		1.9	0.6	1.30	2.50	0.70	3.10	0.10	3.70	3	3	
Lateral	1	Number of fracture lines	4.5	1.3	3.20	5.80	1.90	7.10	0.60	8.40	IFPL01	IFPL03
		Length of fracture lines	265.7	127.7	138.00	393.40	10.30	521.10	-117.40	648.80	6	10
		Size of fragment	33.5	13.8	19.70	47.30	5.90	61.10	-7.90	74.90	197.69	253.25
	2	Location of longitudinal lines									wrong	ok
	3	Medial	2.7	0.9	1.80	3.60	0.90	4.50	0.00	5.40	3	3
		Anterior	2.5	0.7	1.80	3.20	1.10	3.90	0.40	4.60	4	8
		Lateral	4.3	1.2	3.10	5.50	1.90	6.70	0.70	7.90	3	4
Posterior		2.2	0.6	1.60	2.80	1.00	3.40	0.40	4.00	2	2	
Medial	1	Number of fracture lines	3.8	1.3	2.50	5.10	1.20	6.40	-0.10	7.70	IFPM06	
		Length of fracture lines	177.8	123.6	54.20	301.40	-69.0	425.00	-193.00	548.60	4	
		Size of fragment	33.9	16.3	17.60	50.20	1.30	66.50	-15.00	82.80	138.52	10.29
	2	Location of longitudinal lines									ok	
	3	Medial	2.9	1.5	1.40	4.40	-0.10	5.90	-1.60	7.40	3	
		Anterior	2	0.7	1.30	2.70	0.60	3.40	-0.10	4.10	2	
		Lateral	2.3	0.7	1.60	3.00	0.90	3.70	0.20	4.40	3	
Posterior		1.3	0.5	0.80	1.80	0.30	2.30	-0.20	2.80	2		
Posterior	1	Number of fracture lines	2.9	1.7	1.20	4.60	-0.50	6.30	-2.20	8.00	IFPP04	
		Length of fracture lines	165.7	92.8	72.90	258.50	-19.90	351.30	-112.70	444.10	3	
		Size of fragment	0	0	0.00	0.00	0.00	0.00	0.00	0.00	216.03	5.04
	2	Location of longitudinal lines									wrong	
	3	Medial	1.3	0.5	0.80	1.80	0.30	2.30	-0.20	2.80	2	
		Anterior	2.4	1.1	1.30	3.50	0.20	4.60	-0.90	5.70	3	
		Lateral	1.4	0.52	0.88	1.92	0.36	2.44	-0.16	2.96	2	
Posterior		2	1	1.00	3.00	0.00	4.00	-1.00	5.00	2		

Global assessment

In that case, the fracture pattern is catalogued as correct. Although the location of longitudinal lines does not correspond with the statistical data of criteria 2 (lateral impact with longitudinal lines in both medial and lateral aspects), it would be an isolated case, it being necessary to check the remaining criteria. The number of fracture lines on the anterior aspect is in the range of 4.2% of the cases. It is a rare case, but the rest of the criteria are satisfied.

Therefore, performing an analysis of the results obtained with the tool and by the experts, it can be observed that both conclude that the fracture pattern is correct.

b: Validation of IFPA02

Experts validation

The experts find the fracture pattern incorrect, because the fragment is considered too large, otherwise they state that the fracture could be correct due to the polygons formed and the configuration of longitudinal lines.

Automatic validation

According to the automatic validation tool, for the criterion 1, the number of fracture lines and their length are considered correct, but the size of the fragment is not considered correct, due to the large size of the fragment. Criterion 2 shows that the pattern does not present any type of anomaly as far as the longitudinal lines are concerned. Regarding

criterion 3, the number of fracture lines on each aspect is considered correct. The fracture pattern is considered incorrect due to the large size of the fragment.

Global assessment

Finally, it is concluded that automatic validation obtains the same results as the experts, agreeing that the fracture pattern is incorrect.

c: Validation of IFPL03

Experts validation

The experts conflict with this validation. One expert considered this pattern incorrect due to the angles of inclination and configuration of ramifications. The other expert considered that this pattern could be correct, although he thought that there are missing ramifications in the posterior aspect.

Automatic validation

According to the automatic validation the criterion 1, it is concluded that the total number of fracture lines is exceeded. Regarding the second criterion, there is no anomaly in the longitudinal lines. Criterion 3 reveals that for the anterior aspect the number of fracture lines has been widely exceeded.

Global assessment

The above data reveal that this is a more complicated fracture pattern, since the experts themselves differ in their results, so we can see that the automatic validation tool

shows that the fracture pattern is clearly incorrect, clearing the doubts of the experts.

d: Validation of IFPP04

Experts validation

In this case the experts unanimously consider that the pattern is incorrect, because it has a fragment and only one longitudinal fracture line in the anterior aspect. They also point out that the size of the fragment is too small, but this is according to a size of nearly 0 for the fragment. They believe that it is possible to generate a very small fragment in this type of impact, regardless of the statistics.

Automatic validation

According to the automatic validation tool, the first validation criterion shows that two of the three required characteristics are correct, but the fragment size is incorrect. There should be no fragment detachment. Criterion 2 shows that the pattern has anomalies in relation to the longitudinal lines, it has a longitudinal line in the contralateral aspect, but not in the impact aspect. The third criterion shows a correct number of fracture lines on each aspect.

Global assessment

Therefore, the analysis of the results reveals that both the tool and the experts agree that the fragment size is incorrect or that no fragment should appear, so it determines that the fracture pattern is incorrect. Additionally, the tool points out that the longitudinal lines configuration is incorrect.

e: Validation of IFPA05

Experts validation

The experts independently conclude that the fracture pattern should be correct.

Automatic validation

Criterion 1 reveals that the fracture pattern is correct only for one of the three characteristics studied, the number of fracture lines and the size of the fragment are both out of range. About criterion 2, it is satisfied, Regarding criterion 3, the number of fracture lines on the anterior aspect exceeds the limits.

Global assessment

Carrying out a general analysis of the results obtained, it can be seen that the experts differ in the evaluation with respect to automatic validation. The automatic tool determines that the result of evaluating the fracture pattern is incorrect because there are a large number of fracture lines. In addition, the size of the fragment is too small, so the tool shows that the fracture is statistically incorrect while experts believe it is correct.

After consulting with the experts again due to this discrepancy, they agree that the number of branches on the anterior aspect could be too large. They consider that this type of fracture can appear with small branches on this aspect, but they do not appreciate the size of them. The statistics only count the number of branches with a size of less than 1 centimeter. On the other hand, the small size of the fragment reveals

that in some situations the fragment detachment could not be considered in statistics, being unpriced. The tool reveals a greater number of branches, which leads us to conclude that the fracture pattern is incorrect.

f: Validation of IFPM06

Experts validation

The experts independently conclude that the fracture pattern is correct.

Automatic validation

Criterion 1 reveals that the fracture pattern is correct for all the characteristics studied, as the fragment size is a little small, but in the interval of 27.2% of cases. Criterion 2 is satisfied. Regarding criterion 3, the number of fracture lines by aspect are all correct.

Global assessment

Both the tool and the experts agree that the fracture pattern is correct. It is a standard case with no difficulties.

2) VALIDATION OF PARAMETRIC CASES

For each aspect, two valid cases and one invalid case are generated. To be brief, only cases with an explanation or invalid cases are explained in depth. All the cases can be consulted in table 6.

Normally, experts and automatic validation agree on the correctness of fracture patterns. The patterns generated are clear and satisfy the validity criteria. Only in a few cases is an explanation needed. For invalid cases interpretations are provided.

Regarding PFPL02 (Fig. 7e), experts doubt about the number of fracture lines, but the automatic validation concludes that is an extreme case of 8 fracture lines, many of them branches, in the extreme interval of 4.2% of cases, not being relevant for an erroneous fracture pattern conclusion.

Another case is the PFPP01 (Fig. 7j). The experts consider that is a valid pattern and the automatic validation even considering it a valid pattern, the number of fracture lines on the medial and lateral aspects are reduced to zero. This is an extreme case but plausible.

For the invalid case generated PFPA03 (Fig. 7c), experts agree that is an invalid pattern, due to the number of branches, especially on the contralateral aspect. Additionally, the automatic validation includes a further reason, that the size of the fragment is too small.

Analogously, for the invalid case PFPL03 (Fig. 7f), experts consider that the transversal line does not correspond to a valid fracture. The validation tool does not implement this situation, but the number of fracture lines is on the limit of the ranges. Additionally, the automatic validation considers that in the case of lateral impact, there should not be longitudinal lines on both the impact and contralateral aspects.

In the case PFPM03 (Fig. 7i), experts consider it a valid fracture pattern. The automatic validation determines it is an incorrect pattern due to the number of fracture lines. As in the case of the interactive case IFPA05 (Fig. 6e), after consulting the experts again, small branches appear, but they are longer

TABLE 6. Values obtained with automatic validation for the parametric fracture patterns. Red color indicates values out of range, green color values in the 4.20% interval and blue color values in the 27.20% interval.

Direction of impact	Criterion	Statistics		68.20%		27.20%		4.20%		Case			
		Mean	±SD	Inf	Sup	Inf	Sup	Inf	Sup	PFPA01	PFPA02	PFPA03	
Anterior	1	Number of fracture lines	3.6	0.9	2.70	4.50	1.80	5.40	0.90	6.30	5	4	10
		Length of fracture lines	176.6	71.5	105.10	248.10	33.60	319.60	-37.90	391.10	129.55	68.24	147.63
		Size of fragment	48.9	7.7	41.20	56.60	33.50	64.30	25.80	72.00	39.12	36.05	21.88
	2	Location of longitudinal lines									ok	ok	ok
		Medial	2	0.7	1.30	2.70	0.60	3.40	-0.10	4.10	3	1	2
		Anterior	4.2	0.8	3.40	5.00	2.60	5.80	1.80	6.60	3	3	5
3	Lateral	1.8	0.8	1.00	2.60	0.20	3.40	-0.60	4.20	2	1	2	
	Posterior	1.9	0.6	1.30	2.50	0.70	3.10	0.10	3.70	3	2	7	
Lateral	1	Number of fracture lines	4.5	1.3	3.20	5.80	1.90	7.10	0.60	8.40	5	8	8
		Length of fracture lines	265.7	127.7	138.00	393.40	10.30	521.10	-117.40	648.80	139.78	91.65	189.77
		Size of fragment	33.5	13.8	19.70	47.30	5.90	61.10	-7.90	74.90	0.00	34.81	44.61
	2	Location of longitudinal lines									ok	ok	wrong
		Medial	2.7	0.9	1.80	3.60	0.90	4.50	0.00	5.40	4	4	5
		Anterior	2.5	0.7	1.80	3.20	1.10	3.90	0.40	4.60	2	2	4
3	Lateral	4.3	1.2	3.10	5.50	1.90	6.70	0.70	7.90	3	3	5	
	Posterior	2.2	0.6	1.60	2.80	1.00	3.40	0.40	4.00	2	2	2	
Medial	1	Number of fracture lines	3.8	1.3	2.50	5.10	1.20	6.40	-0.10	7.70	6	3	8
		Length of fracture lines	177.8	123.6	54.20	301.40	-69.40	425.00	-193.00	548.60	137.53	111.82	129.90
		Size of fragment	33.9	16.3	17.60	50.20	1.30	66.50	-15.00	82.80	46.28	0.00	54.13
	2	Location of longitudinal lines									ok	ok	ok
		Medial	2.9	1.5	1.40	4.40	-0.10	5.90	-1.60	7.40	4	2	7
		Anterior	2	0.7	1.30	2.70	0.60	3.40	-0.10	4.10	2	3	2
3	Lateral	2.3	0.7	1.60	3.00	0.90	3.70	0.20	4.40	3	2	2	
	Posterior	1.3	0.5	0.80	1.80	0.30	2.30	-0.20	2.80	2	2	2	
Posterior	1	Number of fracture lines	3.8	1.3	2.50	5.10	1.20	6.40	-0.10	7.70	6	3	8
		Length of fracture lines	177.8	123.6	54.20	301.40	-19.90	425.00	-193.00	548.60	137.53	111.82	129.90
		Size of fragment	33.9	16.3	17.60	50.20	1.30	66.50	-15.00	82.80	46.28	0.00	54.13
	2	Location of longitudinal lines									ok	ok	ok
		Medial	2.9	1.5	1.40	4.40	-0.10	5.90	-1.60	7.40	4	2	7
		Anterior	2	0.7	1.30	2.70	0.60	3.40	-0.10	4.10	2	3	2
3	Lateral	2.3	0.7	1.60	3.00	0.90	3.70	0.20	4.40	3	2	2	
	Posterior	1.3	0.5	0.80	1.80	0.30	2.30	-0.20	2.80	2	2	2	
Posterior	1	Number of fracture lines	3.8	1.3	2.50	5.10	1.20	6.40	-0.10	7.70	6	3	8
		Length of fracture lines	177.8	123.6	54.20	301.40	-19.90	425.00	-193.00	548.60	137.53	111.82	129.90
		Size of fragment	33.9	16.3	17.60	50.20	1.30	66.50	-15.00	82.80	46.28	0.00	54.13
	2	Location of longitudinal lines									ok	ok	ok
		Medial	2.9	1.5	1.40	4.40	-0.10	5.90	-1.60	7.40	4	2	7
		Anterior	2	0.7	1.30	2.70	0.60	3.40	-0.10	4.10	2	3	2
3	Lateral	2.3	0.7	1.60	3.00	0.90	3.70	0.20	4.40	3	2	2	
	Posterior	1.3	0.5	0.80	1.80	0.30	2.30	-0.20	2.80	2	2	2	

than 1 centimeter. This aspect was not considered by the experts, who are used to seeing several branches in this type of fracture, but they did not realize the exact size of them.

Finally, the situation of case PFPP03 (Fig. 71), reveals that it is an invalid fracture pattern, due to the apparition of a fragment, when in this type of fracture it is missing according to statistics. Both the experts and the automatic validation, match in this result.

C. FULL CASE VALIDATION

In this section, the set of interactive and parametric fracture patterns generated are analyzed.

For the validation process, a set of 64 fracture patterns have been created using the interactive tool, 16 fracture patterns for each impact aspect. Additionally, a set of 64 fracture patterns have been created automatically giving the appropriate parameters, 16 for each impact aspect. As the fracture patterns created in this form are supposed to be valid, erroneous fracture patterns have been forced (4 erroneous cases and 12 valid fracture patterns for each aspect). In order to do this the input values for the algorithm have been changed to erroneous values, as well as a modification of the algorithm being performed in order to implement erroneous rules. All of these fracture patterns have been checked in the results section, firstly by experts, and then by automatic validation.

For the automatic generation, parameters that fulfil the validation criteria have been provided only for correct patterns. In spite of this premise, erroneous fracture patterns can

TABLE 7. Results of the validation process for the interactive generation.

Measurements	Total	Correct	Incorrect
Automatic	64	35	29
Experts	64	41	23
Concordance automatic and experts	56	34	22
Experts doubts	6	5	1
Experts correction	64	37	27
Final discrepancy automatic and experts	2	2	0

be obtained. This is a desirable option, due to the possible extension of the automatic generation of additional cases and studies. Generation and validation receive a robust system for obtaining valid fracture patterns.

A study of the results obtained by both the experts and automatic validation, is provided for each of the 64 cases of interactive generation and for each of the 64 cases of parametric generation of fracture patterns. The premise about the validity of the fracture pattern is also provided for the parametric generation, its validity for the interactive obtainment of patterns being unknown. In the case of any doubt of one of the experts or discrepancy between them, it has been marked as “doubt”. Finally, the concordance between the experts and the generation is provided, as well as the discrepancy between the premise and the generation for the parametric generation cases.

For interactive generation (table 7), we do not have a premise about the validity or non-validity of the fracture pattern. The automatic validation obtains 35 correct patterns and 29 incorrect patterns. The experts considered 41 correct

TABLE 8. Results of the validation process for the parametric generation.

Measurements	Total	Correct	Incorrect
Premise	64	48	16
Automatic	64	48	16
Concordance premise and experts	62	47	15
Experts	64	47	17
Concordance automatic and experts	57	44	13
Experts doubts	4	3	1
Experts correction	64	47	17
Final discrepancy automatic and experts	2	1	1

patterns and 23 incorrect patterns with doubts or discrepancies between them in 6 cases. 5 doubts correspond to correct cases and 1 doubt corresponds to an incorrect case according to the automatic validation. All the doubts concluded with a correct classification of the automatic validation, obtaining a total of 62 matches between the automatic validation and the experts conclusion. The 2 remaining cases were checked manually, concluding that the experts were right. Checking the results obtained by the automatic validation of those cases we found that some fracture lines were painted with two lines, being counted in this manner as two by the validation tool and one by the experts, thus obtaining a different result. This was caused by an improper use of the interactive tool in some special and controlled situations. Better training and instructions should be given to the users to properly construct the fracture patterns.

In the case of the parametric generation of fracture patterns (table 8), 48 cases have the premise of being valid, while 16 cases are considered as invalid due to the parametric generation performed. The automatic validation matches with the premise in 62 cases from the 64, it fails on one generated as a correct pattern and on one generated as an incorrect pattern, that is, to say it generates the first as an incorrect pattern and the last as a correct pattern. The experts match with the automatic validation in 57 cases, not matching in 4 cases in which the automatic validation obtains a correct result and 3 cases in which it obtains an incorrect result. The experts doubted or were in disagreement with each other in 4 of these cases, but these cases were in concordance with the automatic validation, not being necessary further explanation by the experts about their judgment. The remaining 2 cases have been checked manually with the forensic criteria obtaining the same result as the automatic validation, which confirms that automatic validation works properly.

D. USABILITY STUDY

In the search for an intuitive and easy-to-use product, while the interactive fracture pattern generator has been developed, it has been offered to different types of users with different computer knowledge and age ranges in order to detect the least understandable aspects of the application. With this information the interactive application has been modified in order to achieve a tool as intuitive tool as possible.

A sample of 10 users with different degrees of expertise in traumatology and in the use of computer tools was selected. Two of them were experts in traumatology, additionally four were health professionals, three computer engineers and finally three users with limited knowledge of traumatology or

TABLE 9. Questions with more deviated scores.

Question	Mean	\pm SD
1	3.8	0.42
2	3.6	0.97
3	4.4	0.84
4	4.9	0.31
5	4.0	0.67

computer tools. In order to detect these aspects, the interactive fracture pattern generator was tested by them without explaining in detail how it is used. An image of a fracture pattern was provided to the users and they tried to reproduce this fracture pattern using the tool.

Here we show some of the most relevant questions in the questionnaire of 20 questions (table 10). Questions with more deviated scores or scores below the optimal punctuation are shown in table 9 and figure 8. Scores were in a Likert scale of 1 to 5, with 5 being the best rating.

- **Question:** “*Help is required to perform the requested tasks*”. Users needed help in many cases to use the tool, mainly due to inexperience with computer equipment or inexperience in the area of fracture patterns.
- **Question:** “*Previous knowledge is not needed to performing the required tasks*”. Users with lesser knowledge about the tasks require previous training not for performing the tasks but for understanding the process of fracture. There is a greater deviation, and we think it is due to the variability of specialization of users selected to use the interactive generator.
- **Question:** “*I made mistakes while performing tasks because I didn't read a message or indication from the application*”. Some users do not read the indications given by the interface, so there are semantic errors, although in low proportion.
- **Question:** “*The application has messages or instructions for performing a task that are not clear*”. Most users concluded that the tool was clear, so this question reveals that the interface has no errors in their messages or while performing tasks, as well as the fact that the interface is clear and makes the user feel comfortable.
- **Question:** “*The application is simple to use*”. It is concluded that it is not too complicated to use, as it has a score of 4 out of 5 for usability of the tool, meaning that a great percentage of users believe that it is a simple tool to use.

In general, the mean average obtained from the complete questionnaire is 4.6 with a standard deviation of 0.6, so we can affirm that the tool is completely usable and intuitive.

VI. DISCUSSION

The possibility of having a tool that allows us to generate different fracture patterns, either interactively or automatically, enables us on the one hand to generate a bank of different fracture patterns that otherwise would not be possible to obtain by other means and on the other enables us to study the generated fracture patterns so that we can verify their characteristics and

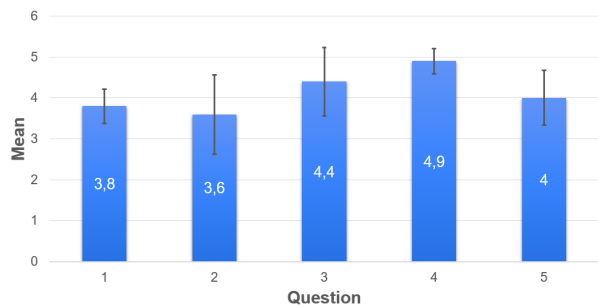


FIGURE 8. Questions with more deviated scores. The black line indicates the standard deviation for each question.

TABLE 10. Usability questions.

Number	Question
1	The application is simple to use
2	I consider the application reliable
3	The application is attractive (combination of colors, legible font size, etc.)
4	I'm comfortable with the use of the application
5	Previous knowledge is not needed to performing the required tasks
6	The steps required to create and modify a fragment are simple and intuitive
7	The sequence of steps for creating an oblique or transversal line are adequate
8	The steps required for generating longitudinal lines or branches are intuitive
9	In general, the steps required for creating a fracture pattern are intuitive
10	The representation of the fracture pattern once finished is reliable
11	I consider excessive the number of steps to complete a task
12	There are ambiguous or incorrect messages and instructions
13	Help is required to perform the requested tasks
14	I needed to use the help of the application to start using it
15	I needed to use the help while using the application
16	The application has messages or instructions for performing a task that are not clear.
17	I made mistakes while performing tasks because I didn't read a message or indication from the application
18	I will use the application again if I have to perform a related task
19	Degree of satisfaction with the application
20	Degree of satisfaction with the result obtained

obtain precise measurement values. The automatic validation of fracture patterns, both generated and real, provides us with an objective and direct means of knowing if the patterns that are generated are correct, or if their parameters are supported by the statistics of forensic analysis studies, so this validation can be expanded to accommodate new emerging studies. These tools can be used for forensic analysis, so information about the causes and parameters that trigger the fracture were included in the study.

The types of fracture patterns that are able to generate the interactive and parametric tools are transversal, oblique or butterfly and longitudinal. Transverse fractures extend with approximately a 90 degree angle from the vertical axis of the long bone, while oblique fractures extend diagonally across the diaphysis. Longitudinal fractures occur when a fracture line follows the longitudinal axis of the bone. The incorporation of spiral fracture patterns will be studied in the future because they are more complex. This type of fracture

is caused by rotation forces in the bone or a combination of torsion and flexion. Comminuted fractures, in which multiple fragments and multiple fracture lines are generated, will also be studied in future.

In some situations experts doubt or obtain a different result about the correctness of the fracture pattern. Automatic validation helps in obtaining the correct result and the clarification of doubts, with an accurate explanation of the features which satisfies the fracture pattern according to the statistics. Usually, the doubts are generated by the size of the detached fragment or the number, position or length of the longitudinal lines and branches. Automatic validation explains and obtains precise measures of these factors, clearing the doubts of the experts with a clear explanation of the results obtained.

We observed that some criteria are never exceeded, such as the length of the fracture lines. This is due to the large standard deviation of this feature. Maybe a new study on the precision of the ranges or intervals should be realized.

The criteria used can be modified or adapted to new situations and further analysis. This led us to count on a versatile and adaptable tool for validating fracture patterns. These criteria use the interpretation of standard deviation as a tool which offers a precision grade on the measures, for an overall validation study which supports extrem and plausible cases.

In the exhaustive study of 64 interactively generated fracture patterns, the automatic validation provides excellent results, with a full concordance with experts. The experts change their criterion in 6 cases marked with doubt and discrepancy with automatic validation, helped by the explanation given in these validations. The 2 remaining cases with discrepancy were resolved with the interpretation of an improper use by users of the interactive generation. Suitable training of users is needed to avoid these situations. Most of the discrepancies or doubts were in incorrect cases. This is due to fine details that automatic validation can examine, being unnoticed by experts, like the length or size of branches and fragments, which led them to consider a correct fracture pattern. Usually when a fracture pattern is catalogued as incorrect by the expert, it is absolutely clear. We can conclude that the interactive generation of fracture patterns offers a suitable manner to design complex fractures in a guided way, assisted with automatic validation in order to obtain correct fracture patterns.

The parametric generation of fracture patterns complements interactive generation in order to provide a quick and effective manner of generating fracture patterns with suitable characteristics. It is possible to parametrize a set of input values for varying the fracture patterns obtained, it being possible to customize and extend the types of fractures and adapt the generator to further forensic studies. Moreover, it is possible to obtain banks of fracture patterns for their use in other disciplines such as, for example, the fracturing of 3D bone models.

The validation of the parametric generation obtains that most of the cases match with the expert's judgment. They disagree only in two cases. We are convinced that the automatic

tool gives a correct result for them, after checking the criteria manually.

The parametric generation of valid cases fails in 1 of the 48 cases, that is, one wrong pattern is obtained when it should be correct. This case is a complex fracture pattern generated with multiple branching lines which is near the limits of the number of fracture lines for the impact aspect, combined with a very small fragment, which is also near the limits of the interval for this characteristic. Numerical inaccuracies combined with rounded integer arithmetic as well as the use of random number generation obtains this singular case. Both, the automatic validation and the experts coincide that this case is catalogued as incorrect. Better precision adjustments should be provided in future versions of the software.

On the other side, the parametric generation of invalid cases fails in 1 of the 16 cases, that is, it obtains correct patterns. We have to consider that the generation of invalid cases has been forced with out of range parameters and variations of code which in some situations obtain correct fracture patterns. These situations can be corrected with the use of parametric generation combined with the use of automatic validation, for discarding anomalous patterns.

The usability study of the interactive generator concludes that users value positively the use of this tool for obtaining fracture patterns, it proving better than other nonspecific drawing tools for this aim. The generator helps and guides the user in the generation of valid fracture patterns, complex training being unnecessary to design correct fracture patterns.

VII. CONCLUSIONS

The interactive generator proposed allows the obtainment of realistic fracture patterns. In addition to generating patterns manually, it is also possible to load other types of patterns and represent them. Moreover, the fracture patterns generated can be validated in an automatic form, according to the criteria extracted from forensic studies which, through an exhaustive study, identify the validity of the patterns according to different metrics. A usability study has been carried out. The results of this study conclude that the tool is simple and intuitive, so in the hands of experts it is possible to make realistic fracture patterns that can be exported to other systems, establishing a new source for obtaining fracture patterns for future studies.

A parametric generation of fracture patterns allows us to obtain an exhaustive bank of fracture patterns that are validated both, by the robust algorithm for the generation and by the automatic validation performed. These fracture patterns can be used in multiple simulations or applications which in some cases are difficult to obtain in reality.

The validation method implemented is totally valid, since in most of the cases the experts agree with the result obtained through the automatic validation tool. In the case where the experts do not agree among themselves, the tool provides another more statistical and technical opinion, so it can be used as a method to tilt the balance to one side or the other in a fully argued way, and can even teach the experts new types

of fracture patterns, which they have never had the chance to deal with and which are totally correct.

Definitely, these tools present a double utility, the generation of valid fracture patterns in guided or algorithmic ways, favoring the obtaining of valid and coherent patterns and as already mentioned, as a validation tool. In the future it could be extended to other cases based on forensic analysis literature. As these studies progress, new features will be incorporated for the generation and validation of fracture patterns.

As a result, it also allows the generation of a bank of validated fracture patterns that can be used in the generation of virtual fractures on bone geometric models, as a master pattern or definitive pattern. These patterns would allow the generation of a parametrized fracture following physical patterns on a model that represents the structure of the bone. Moreover, the generation of a bank of fracture patterns can be used as input in simulators related to traumatology, such as training in fracture reduction among other aspects.

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