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Survey Paper

Computer assisted preoperative planning of bone fracture reduction: Simulation techniques and new trends☆

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ABSTRACT

The development of support systems for surgery significantly increases the likelihood of obtaining satisfactory results. In the case of fracture reduction interventions these systems enable surgery planning, training, monitoring and assessment. They allow improvement of fracture stabilization, a minimizing of health risks and a reduction of surgery time. Planning a bone fracture reduction by means of a computer assisted simulation involves several semiautomatic or automatic steps. The simulation deals with the correct position of osseous fragments and fixation devices for a fracture reduction. Currently, to the best of our knowledge there is no computer assisted methods to plan an entire fracture reduction process. This paper presents an overall scheme of the computer based process for planning a bone fracture reduction, as described above, and details its main steps, the most common proposed techniques and their main shortcomings. In addition, challenges and new trends of this research field are depicted and analyzed.

1. Introduction

The treatment of bone fractures is a very complex task. In the case of simple fractures, those in which a bone is divided into two parts by a single fracture line (Fig. 1), an X-ray image is usually sufficient to plan the surgery properly. On the other hand, comminuted fractures usually generate small fragments and bones can be deformed (Fig. 1). This is because this kind of fractures is usually associated with crush injuries. For comminuted fractures, other scan techniques are necessary to obtain three-dimensional (3D) models of the osseous structures and additional issues which require consideration. Specifically, it is necessary to identify the number of fragments, their size and position, their order of placement and the most suitable fixation devices.

Support systems leverage the process by enabling interaction with a virtual model of bones and fragments, by assisting in the planning of a surgical intervention, by detecting lack of bone tissue and by analyzing different configurations of fixation devices. As a result intervention time can be reduced and potential misinterpretations circumvented, with the consequent benefits to patients' treatment and recovery time (Sugano, 2003; Sikorski and Chauhan, 2003).

There are three main stages that govern the planning of a bone fracture treatment: (1) obtaining an anatomic reconstruction of the bones and fragments from the scanned 3D images; (2) fixing and stabilizing the fragments in order to accomplish an early recovery of mobility; and (3) analyzing the virtual fracture reduction under common bio-mechanical conditions. Nowadays in the literature there exist different studies that provide the simulation of a part of the process of bone fracture reduction (Willis et al., 2007; Cimerman and Kristan, 2007; Okada et al., 2009; Fornaro et al., 2010a). Nevertheless, none of them are able to deal with the entire simulation procedure (generation, planning and analysis) in order to enable the planning of a fracture reduction as we discuss in this paper.

The main aim of this study is to provide the reader with a comprehensive identification of the stages involved in a computer assisted planning of a bone fracture reduction process. It includes an exhaustive review of the literature related to this topic and a description of the main techniques and approaches commonly used to accomplish the complex requirements of these stages. Another contribution of this paper is the discussion of the shortcomings

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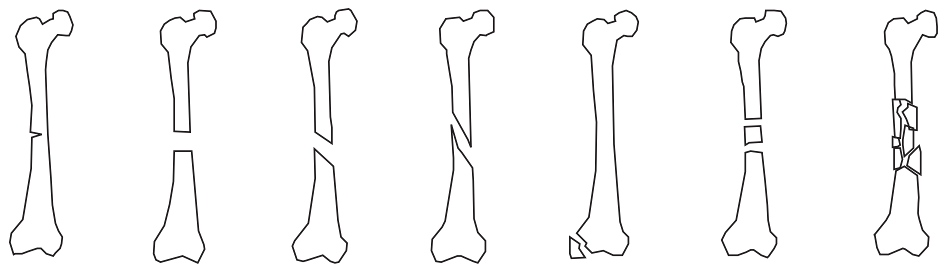


Fig. 1. Fractured bones classified by their fracture lines (Egol et al., 2010).

and conveniences of current methods, the milestones that we face and the horizon regarding computer assisted solutions for the pre-operative planning of a fracture reduction.

This paper is organized as follows: we first present the context surrounding the simulation of fracture reduction and introduce its stages in Section 2. Then we describe the overall process by defining the different stages in a more detailed form (Sections 3–5), indicating the different approaches proposed by the scientific community, their limitations and difficulties as well as future improvements and new trends. Finally, in Section 6 we give our conclusions.

2. Computer assisted preoperative planning of bone fracture reduction

A virtual simulation refers to replicating a model or a process in a computer (Conway and Robinson, 1997). The simulation of a bone fracture reduction involves several processes which are necessary for manipulating and situating the different fragments and fixation devices in order to stabilize a fracture by means of computer assisted techniques. This survey is focused on the study of the available techniques and steps that help in the preoperative planning of a bone fracture reduction, including the analysis of its results. Habitually, the starting point is a set of 3D models generated from medical images, usually computed tomography (CT) images, and, in the end, after solving a 3D puzzle problem, an analyzed stable virtual composition of bone fragments and fixation devices is obtained.

In order to provide a better understanding of the scope of this survey we discuss different terms, situations and objectives of different simulations related to osseous fractures. The aim is to differentiate the scope of this survey from other simulations. Considering the stages of a real intervention as pre-surgery, intra-surgery and post-surgery (Jaramaz et al., 2006) (see Fig. 2), this research is centered on the evaluation of pre-surgery methods that help the specialist in the planning of a real intervention. Intra-surgery execution and post-surgery evaluation are outside the scope of our study.

Taking into account the previous paragraphs, the end of the simulation we are dealing with is to obtain a stable reduction with the fragments and fixation devices analyzed in the computer. Therefore, other treatments like osteotomies or osseointegrated implants are not included. The simulation of osseous fractures is a broader process and there are many other aspects that remain outside the scope of this paper. Other types of simulations are oriented to training, in which usually additional and specific hardware like haptics or 3D stereo glasses are required; or to aiding, which sometimes involves virtual or augmented reality techniques, or the navigation through the real or virtual anatomical model. Both types of techniques are outside the scope of this survey since aiding techniques can be considered as intra-operative and training methods use generic anatomical models and thus cannot be considered planning. Other purposes of the simulation could be the analysis of a fracture or a reduction over time, the analysis of the reduction performed in the surgery, the analysis of the osseous structure in order to prevent a future fracture (fracture risk), or the generation of virtual fractures as a simulation process. However, none of these simulations can be categorized as pre-operative planning, hence all of them fall outside our study (see Fig. 2).

2.1. General view of the stages

Most of the papers reviewed in this survey focus on a specific goal or activity and break down the methods and techniques required to carry it out. However, different activities can share some techniques even in the case of differences in the processes followed in order to achieve their corresponding purposes. For instance, planning and training have common techniques because both require a generation of virtual models, an interactive tool to deal with bone fragments and also analysis of the results. Consequently, one of our main concerns in this survey has been to provide a comprehensive structure to ease the understanding and comparison among the prolific amount of proposals in the literature of the topic. To that end, we have structured our survey according to the computer assisted preoperative planning of the bone fragment treatment process. Similarly, the following sections explain in detail each one of its corresponding stages (see Fig. 3): generation of bone models (Section 3), computer assisted fracture reduction (Section 4), and analysis of a reduced fracture (Section 5). Fig. 3 overviews the methods included in each stage. Now we synthesize each one of the stages which will be explained with more detail in subsequent sections.

The generation of bone models is an artificial step required to generate helpful models to work with in a simulation. The data model used to represent patient information determines the techniques applied at each stage. Different data representations may be necessary, depending on the objectives. Usually, a volume for visualization, a point cloud for fast interaction and a triangle mesh for geometric operations between models. This stage begins with the extraction of osseous tissue from medical images using segmentation and labeling techniques. Then a 3D reconstruction is performed to obtain 3D models of the osseous structures. These 3D models can require optimization techniques in order to obtain adequate representations for the subsequent stages (see Fig. 3).

Focusing on the virtual fracture reduction stage, the main objective is to position and align the bones and fragments, and then stabilize the whole bone structure (see Fig. 3). For this latter purpose, the inclusion of fixation devices is usually required.

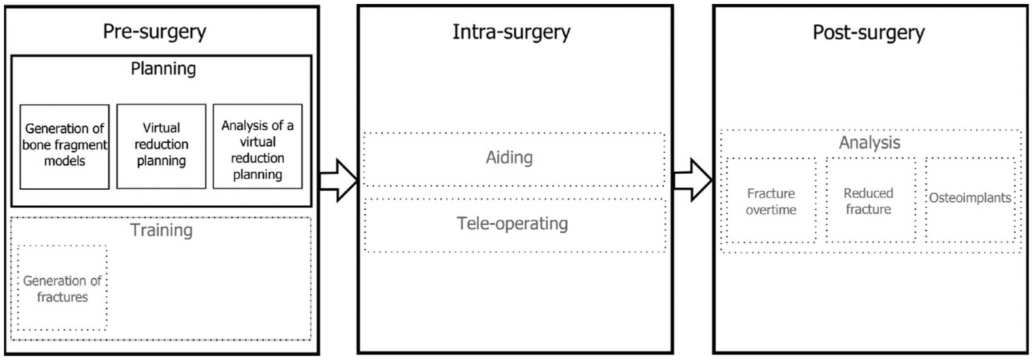


Fig. 2. computer assisted processes that help specialists in a bone fracture reduction surgery. Dotted gray processes are outside the scope of this survey.

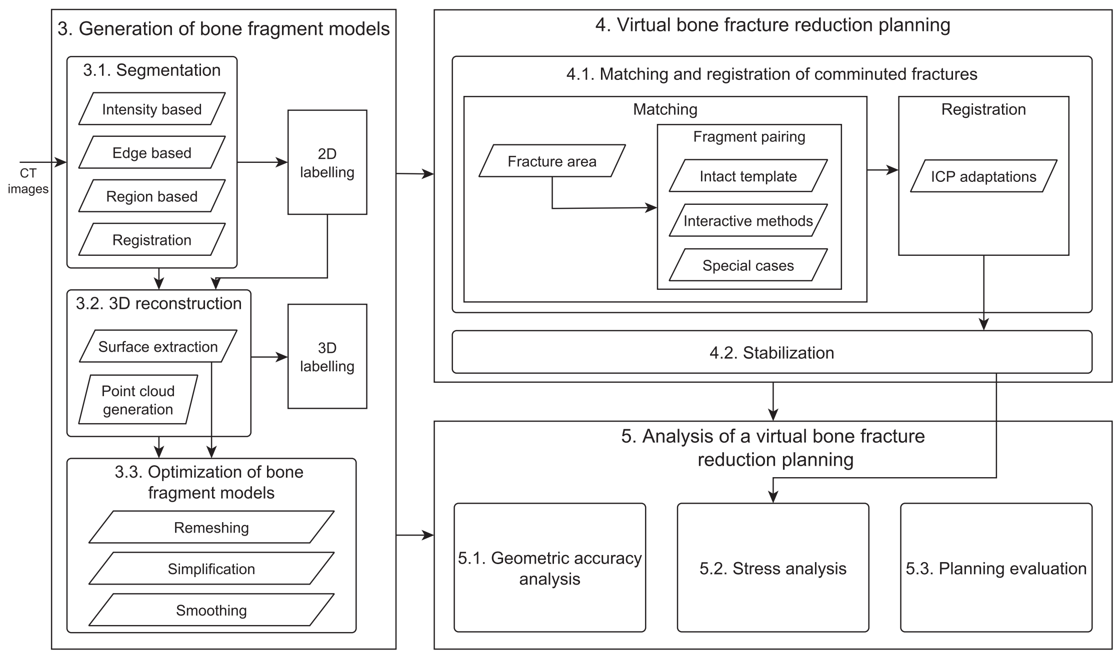


Fig. 3. Detailed view of the stages of computer assisted preoperative planning of bone fracture reduction. The numbers of the corresponding sections are included in the figure.

Depending on their position with respect to the human body, fixation devices can be classified as external, internal or intramedullary.

Finally, fracture reduction analysis is necessary after a virtual fracture reduction in order to validate the result obtained. This analysis can be realized in different ways: obtaining the geometric accuracy of the virtually reduced fracture; using finite element analysis of similar techniques for testing the mechanical stability of the fracture; or even evaluating the simulation process, in this case the planning process, comparing it with a real intervention (see Fig. 3). These stages are further explained in subsequent sections.

At this point it is necessary to note that computer-aided solutions can involve the use of a computer with different degrees of automation. A technique or procedure is considered manual when it is performed entirely by the specialist who plans the surgery. In contrast, a technique is automatic if the computer is able to provide a solution autonomously. At an intermediate term both approaches can be combined in a hybrid solution usually called semi-automatic or assisted. There are many possible degrees of automation in this mixed approach. Commonly, based on his/her experience, the surgeon will design a solution based upon some useful computer-based tools. Some of the reviewed methods can be improved by means of the development of automatic or semi-automatic algorithms.

3. Generation of bone fragment models

This step consists of obtaining 3D models from medical images that represent the bones and fragments involved in a fracture. The representation of these models is diverse and depends on the objectives of the simulation, as previously mentioned in Section 2. For an efficient visualization a volumetric model, a point cloud or a triangle soup can be used. However, for an efficient interaction or in order to perform geometric calculations (i.e. a Boolean operation that simulates an osteotomy), a topologically correct triangle mesh is necessary. Regardless of the model representation, the main goal of this step is to differentiate between bone tissue and other tissues. This process usually includes the labeling or recognition of different bone fragments.

3.1. Segmentation

The segmentation of medical images is usually required in order to obtain the bone regions involved in a fracture. CT images are the most appropriate source used to distinguish bone tissues

Table 1
Summary of the studies on identifying fractured bone which are reviewed in this paper.

Method	Variant	Common applications in references	Advantages	Constraints	References
Registration	Morphon	Hip	Automatic segmentation	Require templates	Pettersson et al. (2006)
Thresholding	Global fixed threshold	Femur and tibia	Simple and fast	Intensity values can differs between slices	Tassani et al. (2012)
	Interactive methods	Humerus, clavicle and scapula	Accuracy	Time consuming	Tomazevic et al. (2010)
Region growing	3D region growing	3D CCL and graph cuts	Labeling performed during segmentation	Interaction can be required to split bone regions in complex cases	Harders et al. (2007); Fornaro et al. (2010b)
	Multi-region growing	Pelvis	Automatic definition of threshold and seeds	Interaction can be required to join or split bone regions in complex cases	Lee et al. (2012)
	2D region growing with seed spreading	Knee joint, fibula, tibia, radius and phalanges	Fragment separation during segmentation	Require additional seeds	Paulano et al. (2014)
Watershed	Probabilistic watershed transform	Tibia, fibula and talus	Incorporate semantic information	Require pre-processing the image and do not specify fragment separation	Shadid and Willis (2013)

from other tissues and thus to perform the segmentation of bone fragments. In the literature, there exist several studies on segmenting fractured bone tissue from CT images. These can be classified into four categories: intensity-based, edge-based, region-based and registration-based. Sachse (2004) made a more detailed description of each category.

The segmentation of a healthy bone from CT images is a complex task that is widely influenced by the type of bone; hence it is difficult to find a solution which works in every situation. In any given bone, two types of tissue may be mainly distinguished: cortical and trabecular tissue. Cortical tissue is very dense and is located on the outer part of the bone. On the other hand, trabecular tissue is mostly located in the inner part of the bone. This type of tissue is more heterogeneous and its intensity is usually lower in a CT scan. The intensity value for the same tissue differs between slices. This happens with both cortical and trabecular tissue. For example, intensity values on the epiphysis and the diaphysis are different in a long bone. Near joints, the cortical area is very thin and even disappears in some regions. This means that some areas within the bone may have similar intensity to the soft tissue surrounding the bone. This can lead to incomplete segmentation or over-segmentation (Lee et al., 2012).

In addition to the intrinsic difficulties of segmenting a bone, a fractured bone is even harder to segment, mainly due to its arbitrary shape and the possibility of fragments belonging to any bone in the nearby area. It is necessary to label all the fragments during the segmentation process, which in some cases requires expert knowledge. Furthermore, a priori knowledge cannot easily be used because it is uncommon to find two identical fractures, especially in comminuted fractures. On the other hand, bone fragments are not completely surrounded by cortical tissue since they have areas on the edges without cortical tissue due to the fracture. Finally, different fragments can appear together due to their proximity and to the resolution of the CT image. For this reason, smoothing filters cannot easily be used in most cases. These types of filters can deform the shape of bone fragments and fracture areas or even remove small bone fragments.

All the currently proposed methods to identify fractured bone from CT images are classified in Table 1. Region-based methods are used in most cases in order to identify bone tissue from CT images. Some methods achieve accuracy at the expense of requiring a lot of user intervention (Tomazevic et al., 2010). The area where bone tissue is located is detected using a threshold-based method. They then proposed manual and semi-automatic tools to interactively segment bone fragments. These proposals include separation, merging and hole-filling tools for generating individually segmented fragments from the previous result. A global fixed threshold method has been utilized by Tassani et al. (2012) to detect the trabecular bone fracture zone. Due to the variation of the intensity levels between slices, it is difficult to find a unique threshold that enables the segmentation of bone tissue in all the slices. Other authors propose pre-processing the image in order to ease the segmentation of bone tissue (Harders et al., 2007; Fornaro et al., 2010b). In these studies a sheetness measure is used to enhance the cortical tissue in CT images. Then the resulted image is segmented using 3D region growing (RG). Fornaro et al. (2010b) apply a 3D connected component labeling algorithm to separate erroneously joined bone fragments in simple cases. To deal with the separation of erroneously joined fragments in complex fractures or in which the boundary of the bone is weak, an interactive graph cut based segmentation is used. Lee et al. (2012) propose a multi-region segmentation approach. Seeds are automatically placed by searching for pixels that have an intensity value higher than a threshold in the image. Then an RG algorithm propagates all the regions in turn. If this multi-region segmentation method fails, the authors provide a manual region combination method that allows blending of the wrongly-segmented regions, and a region re-segmentation method that enables the splitting of wrongly-joined bone fragments. A modification of the classical watershed is proposed by Shadid and Willis (2013). They use Probabilistic Watershed Transform (PWT) to segment bone fragments from CT images, encoding semantic information about the objects. Paulano et al. (2014) show a method based on 2D RG to identify fractured bone from CT images. Similarly to other RG solutions, the algorithm is initiated by a seed placed inside each region of the target bone fragment. These seeds allow the user not only to execute the segmentation method, but also to label the bone fragment. After that, a 2D RG based algorithm is performed for each seed and all the seeds are propagated through the image stack. Since this approach generates a 2D region for each slice, overgrowing can be detected and solved in the first slice where it occurs. For that purpose, an isolated region growing algorithm and a re-segmentation algorithm are proposed.

Other classical segmentation methods, based on edges or registration, are barely represented. Registration-based methods require templates of the fractured parts, hence they are limited to the specific fractures defined by the templates (Pettersson et al., 2006). In addition, it is difficult to find two identical fractures, especially in the case of comminuted fractures. For this reason registration-based methods are limited to simple fractures. On the other hand, edge-based methods try to obtain a closed contour associated with each bone fragment (Willis et al. (2007)). But due to the fracture, bone fragments are partially surrounded by trabecular tissue. This type of tissue is very heterogeneous; hence it is complicated to obtain a closed contour that properly represents the bone fragments.

Table 2
Benefits and drawbacks of optimization methods applying to bone fragment models.

Technique	Input data	Benefits	Drawbacks
Smoothing	Meshes, volumes	Denoise bone fragment models, extrapolate missing information between slices, improve visualization	Small features can be removed from the trabecular tissue, especially in the fracture area and near joints
Simplification	Meshes, point clouds, volumes	Bone fragment models can be processed faster, enable pre-visualization and interaction with huge bone fragment models	Important features can be removed from the trabecular tissue, especially in the fracture area and near joints
Remeshing	Meshes	Better sampling density of bone fragment geometry, improve performance	Difficult to be applied due to the heterogeneity of trabecular tissue

3.2. 3D reconstruction

The main aim of this stage is to provide useful models for simulating the fracture reduction. Depending on the objective of the simulation these models can be volumes, point clouds or meshes. Volumes and points clouds can be easily extracted from segmented CT stacks, hence it is not necessary to detail the technique used to perform this. In some cases the models used are meshes, since simulation methods require geometric algorithms. In order to extract meshes from CT stacks, Marching Cubes (MC) (Lorensen and Cline, 1987) based methods are the most widely used for their simplicity and speed. The size of the models generated by these methods depends on the resolution of the medical images and the complexity of the segmented bone structures. With regard to the generation of fractured bone models, the MC algorithm has been utilized to generate meshes that represent acetabular fractures (Fornaro et al., 2008), fractured pelvic bones (Fornaro et al., 2010b; Lee et al., 2012) and proximal humerus fractures (Fürnstahl et al., 2012). This algorithm has also been used to generate fragment models to represent highly fragmented bone fractures (Willis et al., 2007) and to provide models for a virtual orthopedic surgery simulator (Tsai et al., 2001). Finally, Fornaro et al. (2010a) present an interactive surgical planning tool for reducing acetabular fractures in which models are generated by using a variant of the classical MC algorithm, *the generalized marching cube*.

3.3. Optimization of bone fragment models

The 3D representation of bone fragment models can be post-processed in order to obtain desirable properties for the subsequent simulation stage. Smoothing, simplification or re-meshing are the optimization techniques that are most commonly applied to improve the features of the model and thus enable interaction and improve visualization and manageability. Re-meshing techniques can only be used with mesh-based models; the other techniques can also be applied to point-based and volume models. The models obtained from medical images are usually huge and complex, hence it is very difficult to obtain interactive response time in simulation. Moreover, a re-meshing procedure can be required to obtain a more homogeneous model in order to improve visualization. These optimizations can also be carried out during the generation of the bone fragment models. For instance, the contours extracted during the segmentation process can be simplified to then obtain a smoother mesh. In this subsection we briefly describe the main goal of these techniques and different aspects to be considered when bone fragment models are post-processed. Table 2 shows the benefits and drawbacks of each type of technique regarding models reconstructed from medical images.

The application of smoothing techniques to bone fragment models aims to denoise the area surrounding the bone and extrapolate missing information between slices, improving visualization. This step is especially necessary when the distance between slices is large or the resolution of the image is not good enough, since the reconstructed model can present ripples. Hu et al. (2004) and Engel et al. (2006) present a review of the main methods used to smooth 3D models. Regarding meshes, smoothing functions are able to process vertex positions and normals, considering their connected neighbor vertices, in order to obtain better-shaped models. As a result, the curvature and thus the visual aspect of the model are improved. This type of filters should be used with caution since they can remove not only noise, but also small features from the models.

With the aim of examining the entire fracture area in detail for diagnosis, a large number of high resolution images are required and, as a consequence, the models obtained are big. The required computational cost can easily overwhelm a processor of a common desktop PC and hinder interactivity. In contrast to re-meshing, the simplification of models aims to reduce the size of the models, so minimizing the impact on their morphology and properties. Nonetheless, it is crucial to avoid oversimplification of the bone models in order to preserve their original features. Simplification techniques allow a faster processing and thus enable pre-visualization and interaction with bone fragment models. In contrast, important features can become blurry, especially in the fracture area and near joints. Several studies have been published in order to compare strategies to simplify 3D meshes (Cignoni et al., 1998; Mocanu et al., 2011), point clouds (Pauly et al., 2002) and volumes (Engel et al., 2006).

Re-meshing is a procedure intended to improve the quality of a geometric model. It is a useful technique in the case of models reconstructed from medical images, especially for visualization purposes. The application of this procedure may also involve a simplification of the model, but this is not its main goal. After applying a re-meshing, the quality of the model is enhanced by modifying properties such as sampling density, regularity, size, orientation, alignment or the shape of the models. A complete review of re-meshing techniques is presented by Alliez et al. (2008). A common issue with medical images is the noticeable difference between the distances of two consecutive pixels with respect to the gap between consecutive slices. This is the cause of irregularities in the size and shape of geometrical primitives. In this case, re-meshing techniques can be utilized to enhance the quality of the models and thus their visualization. Nevertheless, re-meshing is difficult to apply in the fracture area and near joints because of the heterogeneity of trabecular tissue.

3.4. Discussion

Considering the revision performed in Section 3.1, the procedure followed in fracture bone identification depends on the bone and the fracture type (Fig. 1). For simple fractures, an X-ray image is usually enough to identify bone fragments and the planning can be manually devised. Nevertheless, in the case of needing computer assisted support, labeling would be necessary, but expert knowledge would not be required. Segmental fractures generate three bone fragments with two separated fracture lines (Fig. 1). Therefore, they can be treated as simple fractures but considering that there are two distinct fracture regions. When identifying a

Table 3
Main features of the proposals for identifying fractured bone which are reviewed in this paper.

Reference	Labeling	Seed or threshold definition	Fragment separation
Harders et al. (2007)	Placing seeds	Interactive seeds and manual threshold	Interactive tools
Fornaro et al. (2010b)	Placing seeds	Interactive seeds and manual threshold	3D CCL and graph cuts
Tomazevic et al. (2010)	Placing 3D seeds	Manual threshold	Interactive tools
Tassani et al. (2012)	Not performed	Interactive threshold	Comparison with healthy models
Lee et al. (2012)	Automatic. A more sophisticated method is only required for erroneously joined fragments	Automatic threshold and seeds	Region re-segmentation
Shadid and Willis (2013)	Automatic	Manual thresholds	Not specified
Paulano et al. (2014)	Placing seeds	Automatic threshold and interactive seeds	Isolated region growing during segmentation

comminuted fracture, some fragments can overlap in the CT image and need additional processing in order to be separated. Labeling is necessary and expert knowledge is strongly required to identify fragments.

The main difficulty in the segmentation step is to identify each one of the fragments deterministically. Currently, this process requires manual user interaction and sometimes expert knowledge, as the already commented comminuted fracture case. This issue is an open research line where previous knowledge would be advisable and more accurate segmentation and labeling methods are needed. With the aim of identifying each of the bone fragments, it is necessary to label them and to separate wrongly joined fragments. On the other hand, the key procedure in the segmentation step is the selection of thresholds and seeds. Table 3 shows how these problems are resolved by each of the proposed approaches. Nowadays the labeling step is in most cases performed manually. As a consequence, both segmentation and labeling can require a post-processing step. Thresholding based approaches do not label bone fragments; hence fragments have to be labeled after the segmentation process. Some approaches try to solve this problem by using seeded based methods (Harders et al., 2007; Fornaro et al., 2010b; Paulano et al., 2014). At the same time that they place the seeds, they identify the bone fragments. Thus, seeds should be placed by an expert. Other studies propose methods to label some bone regions automatically, but then an expert should evaluate the results and decide to which bone or fragment each region belongs. Ideally, all the bone fragments should be segmented automatically and simple bone fragments should be identified without user intervention. Then, in more complex cases, the expert could decide the bone to which each fragment belongs.

Because of the complexity of the trabecular tissue, the selection of threshold intensity values is a challenging procedure. Threshold values are difficult to determine, even manually, and each slice may require a different threshold value. In addition, it is particularly difficult to set the threshold to segment bone tissue near the joints. Most of the proposed methods require that the user manually specify the intensity threshold (see Table 3). The ideal would be that the threshold values were selected automatically from the information available in the set of slices in all cases.

As mentioned in Section 3.1, fragments may require separation during the identification process. The low image resolution can cause very close fragments to appear joined. This is especially common in fractures produced by high energy traumas. Different approaches have been proposed to deal with this problem: interactive tools, 3D CCL, graph cuts, re-segmentation or even comparison with healthy models (see Table 3). Nevertheless, manual and semi-automatic fragment separation takes time, hence automatic methods would be important to enable time-saving. One solution would be to improve the segmentation method, thus joined fragments are avoided. Paulano et al. (2014) presented a semi-automatic method to separate wrongly joined bone fragments during segmentation. A full automation of this process would be profitable, because no additional methods after the segmentation process would be required. However, the usual low resolution of CT scans makes this automation very difficult. An alternative approach would be to directly implement a method to overcome the problem after the segmentation step. Thus, the whole segmented solution is available and additional information can be used from the already segmented adjacent slices. (Paulano et al., 2014; Semelka et al., 2007; Wang et al., 2012; Ji et al., 2013; Hao et al., 2013).

The use of more precise data acquisition technology could avoid fragments appearing together in most cases. In fact, there is a tendency to use μCT images to add extra precision to given regions. Nevertheless, these types of images are not always available and the process of generating them is invasive and has an important radiative impact on the patient (Semelka et al., 2007). Thus, in spite of currently being the best option to distinguish bone tissue, CT scans possess this inescapable drawback. For that reason, alternative scan methods to improve medical images without increasing radiation are mandatory and have become a challenge for the research community. In spite of the fact that the main purpose of medical images is clinical diagnosis, they are also the input of computer assisted techniques that can lead to a reduction of surgery time.

On the other hand, there exist studies that try to segment bone tissue from Magnetic Resonance Imaging (MRI) and X-ray. These techniques require extra information because osseous tissue cannot be identified as well as in a CT scan. Proposed methods are based on an atlas previously constructed from CT images (Wang et al., 2012) or are applied to very specific bone areas (Ji et al., 2013; Hao et al., 2013). However, there are no proposed studies to identify fractured bone from these types of medical image.

With respect to the 3D reconstruction step, the MC algorithm is a de facto standard due to its simplicity and advantageous trade-off for generating surface models. However, this method has several disadvantages that represent a current challenge: the large amount of generated geometry and the lack of topology. In addition, MC generates complex and noisy models. On the other hand, point clouds are easily generated, but they do not avoid the problems for visualizing, managing and interacting with these large models.

The main drawback of using optimization methods is the difference between the processed models and the originally detected bone boundaries. This may cause some fragment bone features, such as fracture surfaces, to become difficult to detect. Paradoxically, smoothing is required to remove undesired ripples whereas at the same time it can blur the boundaries and hinder the extraction, identification and ulterior reduction. However, these techniques are very useful in the visualization process where a level of detail strategy (LOD) can be followed in order to adapt the computational requirements to the specialist's demand.

Table 4
Summary of the studies on reducing complex bone fractures virtually.

Method	Variant	Common applications in references	Advantages	Constraints	References
Interactive tools	Classic 3D interaction	Pelvis, acetabulum and phalanges	Versatility	Time consuming and accuracy	Cimerman and Kristan (2007), Wilson et al. (2009), Hu et al. (2011)
	Haptic interaction	Acetabulum	Haptic feedback	Time consuming	Fornaro et al. (2010a)
Match fracture areas	MWGM	Craniofacial	Automatic fragment matching	Focused on a specific fracture case	Chowdhury et al. (2006), Chowdhury et al. (2009b)
	User directed search	Tibia	Enables multiple potential reconstruction alternatives	Contact surfaces between fragments need to be manually specified	Zhou et al. (2009b)
	Manual	Tibia and fibula	Automatic alignment of comminuted fractures	Matches need to be manually specified	Zhou et al. (2009a), Willis et al. (2007)
	A voting system	Femur	Automatic calculation of fracture areas	Limited to cylindrical bones	Winkelbach et al. (2003a); 2003b)
Register templates	Statistical models	Femur	Does not require the contralateral bone	The results can be influenced by the statistical model	Moghari and Abolmaesumi (2008), Albrecht and Vetter (2012)
	Contralateral bone	Humerus and femur	Accurate reduction by registering fracture lines	Fracture lines extraction requires user interaction	Okada et al. (2009), Fürnstahl et al. (2012)
	Intact template	Tibia and acetabulum	Results can be accurately tested	The intact template is not always available	Thomas et al. (2011), Kato (2013)

4. Virtual bone fracture reduction planning

Virtual bone fracture reduction is the process by which bone fragments are relocated with the aim of recovering their original position. Moreover, in the majority of cases it is necessary to stabilize the fracture by using fixation devices such as plates and screws. This procedure requires resolving a variety of problems that depend on both the type of bone and fracture. In the case of a simple fracture the reduction consists of aligning the two bone fragments in order to recover their original position. If the fracture generates more than two fragments a previous procedure is required to solve the puzzle. For that purpose some approaches propose matching the fracture zones, hence they present algorithms generated in order to calculate these zones. In Section 4.1 the currently proposed approaches to match and register bone fragments in complex fractures are analyzed.

4.1. Matching and registration of comminuted fractures

The reduction of a complex fracture requires finding the correspondence between different bone fragments. It is important to consider that, unlike the reconstruction of plots, bone fracture surfaces may share matches with more than one fragment, hence the matching between fragments may not be one-to-one. In order to complete a fracture reduction all bone fragments have to be translated to their original position. Some of these fragments can be discarded if they are too small to be used in the reduction according to a surgical criterion (Egol et al., 2010). Comminuted fractures usually lead to the deformation of bone structures. These deformations notably increase the difficulty of recovering the original shape of the bone. After the matching procedure, some approaches propose performing a final alignment between fragments in order to improve the result.

All the reviewed studies of complex fractures virtual reduction are summarized in Table 4. Some applications have been developed with the aim of performing a virtual reduction of a comminuted fracture interactively. Cimerman and Kristan (2007) present an application to interactively compose pelvic and acetabular fractures. Acetabular fractures can also be composed by using the software presented by Hu et al. (2011). Wilson et al. (2009) develop an application to manipulate bone fragments reconstructed from CT scans. Due to the complexity of this type of fracture, manual alignment of the fragments becomes a difficult task. In order to make it easier, some authors propose the use of haptic devices (Fornaro et al., 2010a). The haptic feedback provided by these devices eases the correct alignment of the bone fragments. However, this remains a complicated procedure even for an expert.

For that reason, other studies match the bone fragments manually or semi-automatically and then perform a final alignment. Some of these approaches propose matching fracture areas. Willis et al. (2007) propose that the user interactively selects fracture surface patches in pairs that coarsely correspond. Zhou et al. (2009a) propose that the user manually specifies the matching surface regions between fragments. To this end they provide an interactive system that allows the user to manipulate bone fragments, hence the user has to specify fragment surface matches and initiate pairwise and global alignments. Zhou et al. (2009b) describe a new algorithm designed to improve the interactive method introduced by Willis et al. (2007). The algorithm provides a user-directed search in order to match the fragments. To separate fractured and intact surfaces, they use a two-class Bayesian classifier based on the intensity values previously mapped on the surface vertices. Winkelbach et al. (2003b) take advantage of the specific features of long bones. Using a voting system, they calculate the bone shaft axis and the circumference of the long bone fragments and identify the fracture surface. Then an initial solution is computed considering all these calculations. The correct position of the fragments of a broken cylinder structure is also estimated by Winkelbach et al. (2003a). They use a two-step Hough-like voting mechanism to measure the orientation and position of the cylinder axes for each fragment. These methods cannot be applied to the reduction of other types of fractures since they take advantage of the special features of long bones.

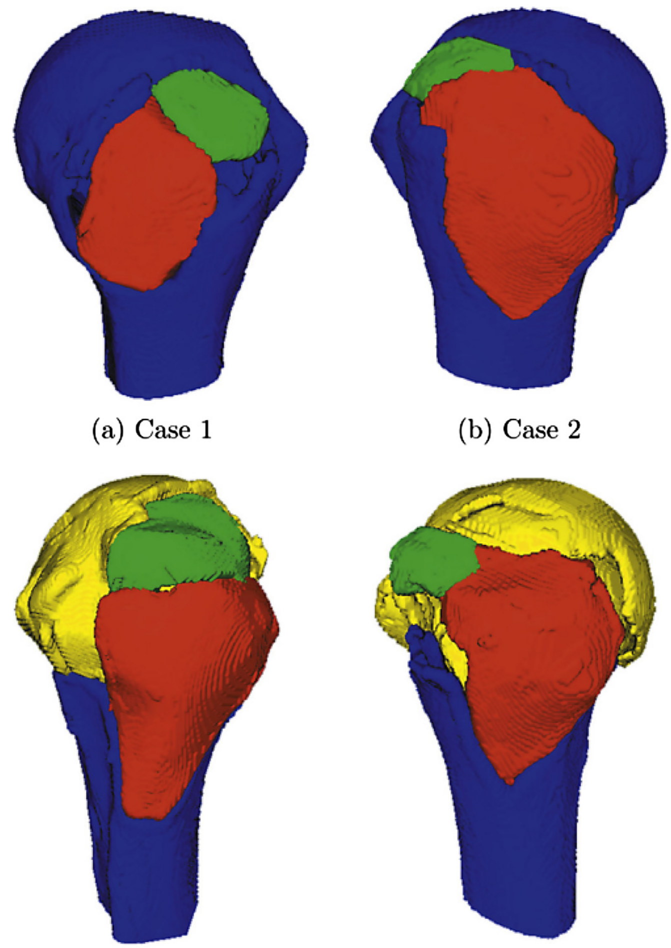
Other proposed studies focus on the reconstruction of complex craniofacial bone fractures (Chowdhury et al., 2006). In this study fracture surfaces are identified using a Maximum Weight Graph Matching (MWGM) algorithm. In this graph, the vertices are the fracture surfaces and the edge weights are treated as elements of a score matrix. A given pair of fracture surfaces will have a high score if they are determined to be spatially proximal and to exhibit complementary fracture surface characteristics. A variation is presented by Chowdhury et al. (2009b). In order to match the fracture fragments, they formulate a matrix score based on the appearance of mandibular fragments in the CT image sequence. As in the study proposed by Chowdhury et al. (2006), a pair of fracture surfaces has a high matching score if they are determined to be proximal and they exhibit complementary fracture surface characteristics. They then propose using the MWGM algorithm to identify the fracture surface pairs in polynomial time. To calculate the correspondence for a given pair of fracture surfaces they use the MCMW bipartite graph matching algorithm.

Finally, complex fractures are also reduced virtually by using a healthy bone as a template. In these studies the contralateral bone (Okada et al., 2009; Fürnstahl et al., 2012), an artificially constructed bone (Thomas et al., 2011) or a statistical bone (Moghari and Abolmaesumi, 2008; Albrecht and Vetter, 2012) are used to perform the initial alignment. These approaches are restricted to the bones defined by the templates and, in most cases, require prior work to generate the artificial bone. Moreover, recent studies have shown that the contralateral side should be used with caution as a template or even as a ground truth because differences in shape can exist between symmetrical bones (Letta et al., 2014).

Okada et al. (2009) study and evaluate several methods for positioning bone fragments of proximal femur fractures. The proposed methods are based on the registration of the bone fragments using the contralateral bone shape, fracture lines or both simultaneously. In order to obtain fracture lines in each slice, they use curvature analysis. Then an interactive line-tracking software allows them to extract the fracture zone from the generated 3D curvature image. Fürnstahl et al. (2012) present an approach developed to reduce humerus fractures virtually (see Fig. 4). For that purpose they use the contralateral bone to register the fragments by using Iterative Closest Point (ICP).

(Thomas et al., 2011) generate identical tibias from blocks of high-density polyurethane foam and fracture them into 10–15 pieces by using an instrumented drop tower. These tibias are scanned before and after being fractured in order to use them as a template and to test the accuracy of the reconstruction. After that, the fracture is composed by matching each native surface to the intact template using an iterative registration function built into the Geomagic Studio Software (Geomagic, 2015). Moghari and Abolmaesumi (2008) generate an atlas by using the principal component analysis (PCA) in a bone population generated from CT scans. Afterwards a local registration is performed for each bone fragment. Albrecht and Vetter (2012) also propose using a statistical shape as an intact template when a contralateral bone or the bone before being fractured is not available. In that case they use the ICP algorithm to perform a rigid alignment of the fragments and then they adapt the statistical shape model to the bone fragments. Due to the fact that the adaptation is only possible if the fragment is already aligned and the rigid alignment depends on the model adaptation, the authors propose solving these two steps simultaneously in an iterative scheme. The registration algorithm requires a roughly initialization. For that purpose, they use the shape models mean bone. Kato (2013) propose performing the fracture reduction by aligning the fragments to a template. For that they formulate the problem as an affine puzzle.

After the matching procedure, most of the proposed studies perform a final alignment in order to fine-tune the result (see Table 5). In many cases this alignment is performed by registering fracture zones to each other. These fracture zones can be surfaces (Winkelbach et al., 2003a; Willis et al., 2007; Moghari and Abolmaesumi, 2008; Zhou et al., 2009b), lines (Okada et al., 2009; Fürnstahl et al., 2012) or points Chowdhury et al. (2006); 2009b), depending on the models used to represent bone fragment and the techniques applied to calculate the fracture zone. In other cases the final alignment is performed by reversing the process and adapting the template to the shape of the initially aligned fragments (Albrecht and Vetter, 2012). This approach is more robust for missing and deformed fragments, but the results obtained rely on the template used. In order to perform the registration an ICP-based algorithm is utilized in most cases (Winkelbach et al., 2003a; Chowdhury et al., 2006; 2009b; Willis et al., 2007; Okada et al., 2009; Zhou et al., 2009b; Thomas et al., 2011; Fürnstahl et al., 2012; Albrecht and Vetter, 2012). As an alternative, Moghari and Abolmaesumi (2008) use an Unscented Kalman Filter-based registration.



(a) Case 1 (b) Case 2

(c) Case 3 (d) Case 4

Fig. 4. Virtual fracture reduction of four complex fractures of humerus performed by Fürnstahl et al. (2012). Authors used a different color to represent each fragment. Initially, fragments are placed in their correct position by registering them to the contralateral bone. Then fracture lines are interactively calculated and registered to each other in order to achieve the final alignment.

4.2. Stabilization

After a virtual fracture reduction, the next step can be to place fixation devices in order to stabilize the fracture (Fig. 5). This procedure requires the user to decide which fixation devices will be used, select their location, and adapt them to the shape of the bone. Current approaches perform this procedure interactively. (Cimerman and Kristan, 2007). Cimerman and Kristan (2007) suggest to manually choose plates and screws. Then, contouring of the plate is performed automatically and the screws can be interactively inserted into the plate or across the fracture. In order to ease this process bones can be made more transparent.

Table 5
Main features of the proposals for reducing complex bone fractures virtually.

Reference	Level of automation	Templates required	Final alignment
Winkelbach et al. (2003a)	Automatic	No	Apply modified ICP to fracture areas
Chowdhury et al. (2006)	Automatic	No	Matching points are calculated using MCMW and registered using a modified ICP
Cimerman and Kristan (2007)	All the process is interactive	No	Manual
Willis et al. (2007)	Fragment matches are manually specified	No	Apply modified ICP to fracture surfaces
Moghari and Abolmaesumi (2008)	Automatic	Statistical atlas	Fractures are registered to each other using an Unscented Kalman Filter-based registration
Okada et al. (2009)	Fracture lines are manually extracted	Contralateral bone	Apply ICP to fracture lines
Zhou et al. (2009b)	User directed fragment matching	No	Apply modified ICP to fracture surfaces
Chowdhury et al. (2009b)	Automatic	No	Matching points are calculated using MCMW and registered using a modified ICP
Fornaro et al. (2010a)	All the process is interactive	No	Manual
Hu et al. (2011)	All the process is interactive	No	Manual
Thomas et al. (2011)	Manual rough alignment may be required	Artificial intact template	Fragments are registered to the template using ICP
Fürnstahl et al. (2012)	Fracture lines are manually corrected	Contralateral bone	Apply ICP to fracture lines
Albrecht and Vetter (2012)	Automatic	Statistical shape model	Fragments are registered to the template using a modified ICP
Kato (2013)	Automatic	Intact template	Align fragments to template by solving an affine puzzle

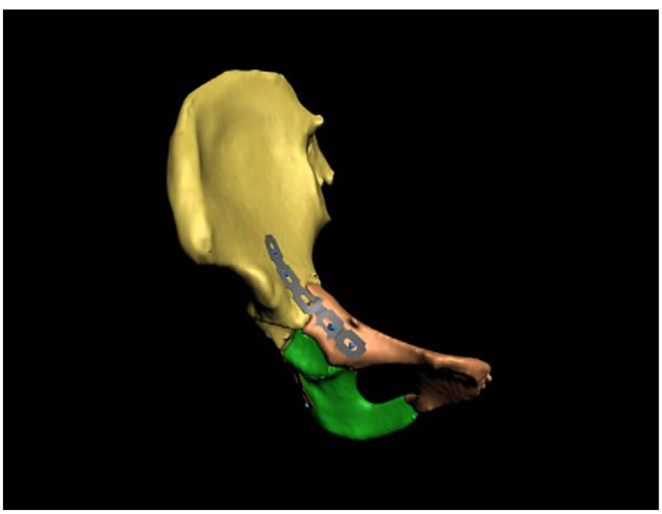


Fig. 5. Acetabular fracture virtually stabilized by Hu et al. (2011). First fragments are placed in their correct position using interactive tools. Then fixation devices are generated using 3D commercial modeling tools and settled across the fracture.

Hu et al. (2011) propose using a commercial 3D modeling tool to generate plates and screws and place them across an acetabular fracture.

Other studies propose a semi-automatic procedure to determine the type of fixation used and its position. Fornaro et al. (2010a) present a surgical interactive tool that enables the adaptation of appropriate osteosynthesis implants onto reduced virtual pelvis fractures. In order to achieve this the user first draws a sketch of the desired plate placement directly onto the bone surface using a haptic device. The system then automatically contours the tetrahedral model of a reconstruction plate of a user-selected type onto the virtual bone surface according to this sketch. Thereafter, the user can place screws of different lengths either through plate holes at angles restricted by the type of implant or freely into the pelvic bone. Thus, a report is generated including relevant measurements and type and size of osteosynthesis implants, as well as bending and torsion angles of fixation plate segments in all three planes. Finally, the surgeon uses this information to manually contour osteosynthesis implants preoperatively according to the report. Results show a generally very good match between planning and final execution. However, some plates could not be placed exactly as planned because soft tissue interfered with the placement of the screws and hence the plate had to be tilted slightly.

Musuvathy et al. (2011) propose a new method of customizing fixation plates to repair bone fractures. In order to avoid the manual adaptation of polygonal plate models to the bones of patients they propose a semi-automatic adaptation of parametric CAD models using NURBS to generate customized plates. Thus, the plates conform to the desired region of the bone surface of patients. This enables an efficient and accurate approach that is also computationally suitable for interactive planning applications. Moreover, the patient-specific customized plates can then be produced directly from the adapted CAD models with a standard CNC machine before surgery. This may dramatically reduce the time spent in the intervention, improve precision of the procedure and, as a result, improve the outcome of patients.

In Liu et al. (2014) a modeling and visualization system for assisting surgeons in correctly registering for the closed fracture reduction surgery is presented. The ultimate aim of their proposal is obtaining the main geometric parameters of the fixation plate. For that purpose, the 3D model of the plate is fitted by using an accurate NURBS-based free-form surface fitting method. Chen et al. (2014) present an interactive tool to plan humeral shaft fractures using a semi-automatic fragment reconstruction approach. Fracture fragments are reduced anatomically by selecting three characteristic points through a manual operation. Finally, the appropriate plates are chosen from the internal fixation devices database of the system.

Intramedullary nail (IMN) is a fixation device which is placed in the medullary cavity of the bone. In IMN surgical operations, one of the main tasks for surgeons is to know the positions and orientations of distal locking holes (DLHs). This procedure is necessary for the insertion of distal transverse interlocking screws. The distal holes on an IMN, which are inside the intramedullary canal of the bone, can only be seen in a lateral X-ray view. For the standard surgical procedure the localization of the distal hole axes is a trial-and-error process which results in a great use of surgical time and a large dose of X-ray exposure. Zhu et al. (2002) present an algorithm designed to derive the 3D position and orientation of the distal hole axis. The algorithm first derives the nail axis through two X-ray images. Then the distal hole axis is calculated by projecting back the hole boundary onto the X-ray image from a lateral view to the 3D space. A least squares method is used to determine the centers of the front hole and the back hole iteratively. Zheng et al. (2008) present an approach for solving this problem based on two calibrated and registered fluoroscopic images. The problem is formulated as a two-stage model-based optimal fitting process. The first stage, nail detection, automatically estimates the axis of the distal part of the IMN by iteratively fitting a cylindrical model to the images. The second stage, pose recovery, resolves the translations and the rotations of the DLHs around the estimated axis by iteratively fitting the geometrical models of the DLHs to the images. An iterative best matched projection point algorithm is combined with random sample strategies to effectively and robustly solve the fitting problems in both stages.

4.3. Discussion

The steps performed to reduce a fracture depend on the fracture type. Greenstick fractures are not usually operated and the damaged area is not immobilized (Egol et al. (2010)). For other fractures the required steps depends on the number of fragments generated. For simple fractures, the reduction procedure consists of aligning the two bone fragments in order to place them in their original position. In a virtual simple fracture reduction, interactive methods allow the user to find the original position of the fragment. However, these methods require a lot of time and obtaining accurate results is difficult. Since the complexity of the reduction of a simple fracture is not great enough to need to perform it interactively, the main goal of these methods is to provide a system which can perform a less invasive operation. This type of surgery reduces infection risk and recovery time.

The revision performed in Section 4.1allows us discussing about the existing approaches in the literature for computer assisted fracture reduction regarding comminuted fractures. As shown in Table 4, most of the proposed works are focused on long bones (tibia, fibula, femur and humerus) (Winkelbach et al., 2003a; Willis et al., 2007; Moghari and Abolmaesumi, 2008; Zhou et al., 2009b; Okada et al., 2009; Thomas et al., 2011; Albrecht and Vetter, 2012; Fürnstahl et al., 2012). In a long bone, the diaphysis is cylindrical and is completely surrounded by cortical tissue. In contrast, the cortical zone in the epiphysis is very thin; hence trabecular tissue can even appear in the outer part of the bone. Therefore, this extra information has favored the development of computer assisted techniques to help specialists to reduce long bone fractures. On the contrary, only just interactive tools have been proposed with the aim of reducing fractures of irregular bones (Cimerman and Kristan, 2007; Wilson et al., 2009; Fornaro et al., 2010a; Hu et al., 2011). As an exception, Chowdhury et al. (2009b) present an approach to reduce craniofacial fractures by calculating, matching and registering fracture zones, and Kato (2013) proposes to reduce acetabular fractures using a template.

Table 5 summarizes the main features of the approaches proposed to virtually reduce bone fractures. We check the level of automation, the necessity of previous information and the strategy used to perform the final alignment. Automatic methods require extra information in order to avoid user interaction. Most of the proposed approaches use templates in order to match bone fragments (Moghari and Abolmaesumi, 2008; Albrecht and Vetter, 2012; Kato, 2013). Others take advantage of differentiable features of a specific bone. Winkelbach et al. (2003a) propose a method to automatically reduce comminuted fractures of femur. For that purpose, authors make use of the special features of long bones already mentioned in the previous paragraph. Chowdhury et al. (2009b) present an approach to automatically reduce craniofacial fractures. In this case, authors take advantage of a previous classification of fragments as terminal or non-terminal, based on the presence or absence of condyles. Nowadays, there is not a method to automatically reduce comminuted fractures that could be applied to any bone. Regarding the final alignment, most of the proposed works use an adaptation of the ICP algorithm. The main drawback of this method is that local solutions can be obtained. Therefore, a previous coarse alignment of the bone fragments is required. The development of more robust registration methods to reduce the obtainment of local solutions would lead to the achievement of more automatic approaches.

The stabilization of a fracture reduction is a key step in the process of guaranteeing the fixation of the fragments in a long-term period. However, at the moment automatic stabilization is almost an unexplored field. Nonetheless, several user-interaction solutions have been proposed to help the specialist to plan the surgery and accelerate the whole process. This lack of general solutions is due to intrinsic technical difficulties, to the necessity of expert knowledge and to the requirement of precise analysis of fracture reduction. During the simulation, plates and screws have to be defined according to the fracture. If plates are virtually designed, they must be later manufactured specific to the patient. Notwithstanding that some of the proposed approaches have been tested in clinical cases, implant manufacturing is still an expensive process. Thus, current solutions propose to contour standard implants in most cases.

5. Analysis of a virtual bone fracture reduction planning

Once a bone fracture has been stabilized, it is useful to check the goodness of that stabilization. In order to check this goodness an analysis of the fracture reduction can be performed. This process mainly consists of simulating the stress produced by the movement of the human body over all the elements involved in a fracture reduction: fragments and fixation devices. Nevertheless, this analysis can be accomplished using different procedures. One of these may be to compare the result of the fracture reduction (omitting the stabilization) with a healthy bone, the bone of another patient or the symmetrical bone of the patient. On the other hand, the whole process carried out by the specialist to virtually reduce the fracture can be evaluated. However, this evaluation procedure can only be applied to interactive and semi-automatic approaches. Finally, numerical and computational techniques can be used to estimate the mechanical stability of a reduced fracture after inserting fixation devices.

5.1. Geometric accuracy analysis

In order to measure the geometric accuracy of the fracture reduction performed, most of the proposed methods compare the results obtained with the ground truth. Ron et al. (2002) determine the usefulness of their method of reducing femur fractures based on the periaxial rotation. To this end, they compare the value of the broken femur to the value of its mirror image. For that purpose they use both real and cadaver data. If the composition is successful, periaxial rotation values should be equal. Moghari and Abolmaesumi (2008) also use bones of corpses, which are artificially fractured to evaluate their femur fracture reduction based on an atlas. Fürnstahl et al. (2012) use both cadaver bones and real clinical cases to measure the accuracy of their proposed method for reducing humerus fractures.

A synthetic material with a mechanical behavior very similar to cortical bone, with similar appearance in X-ray and prone to breaking into fragments in equal numbers and form is used by Zhou et al. (2009b); 2009a) to evaluate their method

Table 6
Summary of the studies analyzing the geometric accuracy of virtually reduced fractures.

Method	Variant	Common applications in references	Advantages	Constraints	References
Compare to the ground truth	Cadaver bones artificially fractured	Femur and humerus	Fractures can be simulated with great veracity	Hard to obtain bones of corpses	Ron et al. (2002), Moghari and Abolmaesumi (2008), Fürnstahl et al. (2012)
	Synthetic fractures	Femur and tibia	Easier to obtain than bones of corpses	Differences between the synthetic and the real bone may exist	Winkelbach et al. (2003a), Zhou et al. (2009b), Zhou et al. (2009a), Thomas et al. (2011)
	Virtually generated fractures	Zygomatic bone, radius and femur	Different test cases can be generated using only one real bone	It is difficult to properly generate a real fracture	Maubleu et al. (2006), Gong et al. (2009), Okada et al. (2009), Albrecht and Vetter (2012)
	Contralateral bone	Femur	Contralateral bone models are obtained easily	Bones are not completely symmetrical	Ron et al. (2002)
Compare to manually reduced fracture	Calculate translational and rotational errors	Femur	Tested fracture cases are real	Manual reduction may contain error	Winkelbach et al. (2003a), Okada et al. (2009)
Calculate parameters after the reduction of real cases	MSE of the registration and matching scores	Craniofacial	Tested cases are real	Results are not evaluated using the ground truth	Bhandarkar et al. (2007), Chowdhury et al. (2009a), Chowdhury et al. (2009b)

for reducing highly comminuted bone fractures. Blocks of high-density Polyetherurethane foam are also used to test the platform for solving comminuted articular fractures presented by Thomas et al. (2011). To test the reduction of cylindrical bone fractures, Winkelbach et al. (2003a) compare the results obtained with virtual manual repositions of the reconstructed bone fragment surfaces using synthetic bones.

To validate the composition of zygomatic fractures, Maubleu et al. (2006) remove the bone from healthy patients virtually and then apply their proposed method. Gong et al. (2009) generate random synthetic fractures in order to test their proposed method. By doing this, they can evaluate the error. Virtual fractures have also been randomly generated in order to test the method proposed by Albrecht and Vetter (2012). Other studies use not only virtual fractures but also real fractures to measure the quality of a fracture reduction method (Okada et al., 2009). In this study they measure the femur reduction from the rotation error of a fragment and the distance between the points that correspond with the fracture area of two fragments.

In cases in which alignment of the fragment is performed by registering the points belonging to the fracture surface, the error in approximating the points can be used as a measure of the quality of the reduction. Bhandarkar et al. (2007) use the Mean Squared Error (MSE) to measure the goodness of the reduction carried out using ICP, DARCES and a hybrid approach. This measure is also used by Chowdhury et al. (2009a); 2009b) to determine the accuracy of a craniofacial reduction. Table 6 summarizes all the studies reviewed that analyze the geometric accuracy of virtually reduced fractures.

5.2. Stress analysis

In recent years, various studies have been presented that attempt to measure the stability of fracture reduction after the insertion of fixating elements. The stability of the bone fixation is an important aspect in fracture healing. In this section, three types of fixating elements have been considered: external fixations, intra-medular fixations and screws and plates. In order to test the mechanical stability of the fracture, numerical and computational techniques are used. Specifically, most of the methods reviewed are based on finite element analysis (FEA) (Poelert et al., 2013). Nowadays, the use of FEA in the assessment of a reduced bone fracture is very time consuming because it requires a lot of manual intervention in order to build and define FE models. Therefore, most of the proposed studies do not use models reconstructed from medical images of clinical cases, but generic models or models reconstructed from corpses in order to test the suitability of the fixators.

5.2.1. External fixation

External fixation is a method for stabilizing bone fractures whose elements are partially placed outside the skin of the patient. Several studies test the stability of this type of fixing devices. Videla et al. (2002) present the analysis and design of new fixation prototypes for open-bone human fractures. These prototypes are based on 3D modeling and FEA. Fixatives are then manufactured by using different materials such as surgical steel, aluminum alloys and reinforced plastics. As a result, light apparatus were obtained and successfully used in real-life situations. Kluess et al. (2009) present a validation method for orthopedic implants based on FEA. By combining several software packages, they convert the initial CT slices into a Finite Elements (FE) mesh in order to test the differences of using tetrahedral and hexahedral elements. They conclude that hexahedral elements perform better with a minor computational effort, but their creation is more complicated. They also demonstrate better performance than directly using Young's moduli by applying temperature dependent material models in combination with Hounsfield units treated mathematically as temperatures. Roseiro et al. (2014) studied the stability of external fixator systems for transverse fractures. They evaluated stability using a simplified 1D finite element model for the tibia and an external fixator. The VABS (Variational Asymptotic Beam Section analysis) methodology is used to compute the cross-section of the generalized Timoshenko model, which was embedded in the finite element solver FEAP. Optimal design is performed with respect to the assembly of fixator components using a genetic algorithm. The optimization procedure is based on the evaluation of an objective function, which is dependent on the displacement at the fracture focus. The initial and optimal results are compared by performing a 3D analysis, for which different three-dimensional finite element models are created.

Table 7
Summary of the proposals to analyze plate and screw fixations using FEA.

Reference	Evaluation set	Analysis performed
Cegoñino et al. (2004)	Distal femur	Compare three different implants
Lin et al. (2006)	Distal radius	Angles between plates
Valentini et al. (2007)	Articulations	Stress distribution in an internal fixation device
Haase and Rouhi (2010)	Femur	Effects of plate and screw parameters on the level of stress shielding in bone
Peleg et al. (2010)	Proximal femur	Performance of the principal strain fixation ratio measure
Bodzay et al. (2011)	Pelvis	Vertical and rotational stability of unstable type C pelvic ring injuries
Wongchai (2011)	Femur	Stress distribution in the 14-hole DCP
Hsu et al. (2012)	Femur	Best screw configuration
Wieding et al. (2012)	Femur	Approaches to model screws
Wongchai (2012)	Femur	Effects of 8 configurations of the screw fixation and DCP

5.2.2. Intramedular fixation

Intramedullary fixation devices can also be analyzed to assess their performance in specific clinical cases. Marasco et al. (2012) analyze and model the physiological forces acting on posterior rib fractures and evaluate the suitability of an intramedullary screw fixation technique. To that end, computerized FEA is used to model a typical sixth rib and analyze the physiological forces that act on the rib in vivo. A fracture in the posterior aspect of the rib is incorporated into the model and an intramedullary screw fixation concept evaluated, using both a bioabsorbable polymer screw and a stainless steel screw. A group of patients with flail chest are reviewed and identified as having multiple posterior rib fractures with displacement. These patients form a clinical correlation group by which to evaluate the FEA model. As a result, FEA modeling of the posterior rib fracture shows likely posterior displacement in response to physiological forces. A review of the patients with flail chest and displaced posterior fractures confirms the direction of displacement. Modeling of an intramedullary screw fixation shows significant stresses in the bone/screw contact areas (stainless steel solution) and the prosthesis itself (bioabsorbable polymer solution). As a conclusion, the FEA model demonstrates that physiological forces cause posterior displacement at posterior rib fracture sites. Fixation solutions designed to counteract these forces need to overcome significant stresses at both the bone/prosthesis contact regions and within the prosthetic material itself.

5.2.3. Plates and screws fixation

Internal fixation is a surgical intervention that involves the implementation of internal fixatives for the stabilization of a reduced fracture. The most frequently used fixating elements are plates and screws and most of the studies reviewed focus on this type of fixative.

The mechanical stability of a fixated fracture has been estimated in several papers (see Table 7). Duda et al. (1998) present a method for determining the 3D stiffness of fracture fixation devices in order to predict inter-fragmentary movement as a function of fracture location and fixation mounting. To do that they utilize a 6×6 stiffness matrix which completely describes the linear relationships between the 6 inter-fragmentary movements and the resulting bone loading. The objective of Valentini et al. (2007) is to analyze the stress distribution in an internal fixation device which consists of a conical join between the plate and the screws connected through a titanium insert. To that end they use bi-dimensional asymmetric and 3D Finite Elements Methods (FEM) to calculate stress distributions for two typical loading conditions: screw tension (to simulate tightening) and screw bending (to simulate device-opening conditions). From the FEM simulation results, they conclude that the most critical area is the screw neck. Moreover, the titanium insertion situated between plate and screw helps to achieve a good stress distribution in the plate and thus to reduce the stress-shielding phenomena.

Haase and Rouhi (2010) use FEA to generate a simplified 3D model of a transverse femoral fracture affixed with a plate. Firstly, they perform a study in order to measure the accuracy of using FEA. Afterwards they conduct a parametric study in order to check the effects of plate and screw parameters on the level of stress shielding in bone. They demonstrate that the reduction of the implant flexural rigidity by limiting plate thickness and angle helps to reduce stress shielding. Moreover, the stress in and around the fracture zone can also be reduced by a change in the distal screw position. Bodzay et al. (2011) compare the stability of 4 surgical methods to treat vertically and rotationally unstable type C pelvic ring injuries. With this aim, joins and mechanically important ligaments are modeled and an FEA is performed using ALGOR software. They measured the displacement between the 2 surfaces of the fracture gap and compared it to the results of measurements performed on cadavers. They concluded that trans-sacral plating generates more displacement than direct plating.

Wongchai (2011) analyzes the stress distribution in the 14-hole Dynamic Compression Plate (DCP) along a femur bone fracture by using FEA. The configuration of the screw fixation plays a major part in DCP stress. Thus, eight configurations of the screw fixation with different body weights are studied. In addition, the maximum von Mises stress on the DCP in each configuration is used to find the best of the screw fixations. The equations of the maximum von Mises stress are formulated by regression analysis. The experimental results show that the relation of the maximum von Mises stress and the number of screws is a linear equation. Therefore, they conclude that maximum von Mises stress from FEA could be predicted by using the linear equation.

Other studies help to decide the best fixation device configuration to stabilize a specific type of fracture. Cegoñino et al. (2004) model three different types of FE mesh to represent different plates and screws. These fixation devices are evaluated according to the stability provided after a distal femur fracture reduction. Specifically, Cegoñino et al. (2004) utilize FEM to evaluate the stability induced in three different types of fractures of the distal femur by three types of implants: condyle Plate, Less Invasive Stabilization System (LISS) and Distal Femur Nail (DFN). For that purpose, the FE model is created from CT images. Their results show that the three types of implants lead to similar results regarding stability. Nevertheless, LISS produce an important resorption in the cortical layer just on the fractured zone. On the contrary, the other two implants do not strongly modify bone tissue microstructure. Lin et al. (2006) present an FE study to analyze a double-plating fixation for a distal radius fracture. The 3D FE models of the distal radius fracture and buttressed plates are generated based on CT data. FE models are generated with commercial software using quadratic tetrahedral elements. Then 9 FE models with three angles between two buttressed plates and three load conditions are simulated. After model verification and validation, frictional (contact) elements are used to simulate the interface condition between the fixation plates and the bony surface. Finally, using FEA the study shows quantitative evidence to identify that much larger plate fixation angles could provide better mechanical strength to establish favorable stress-transmission and prevent distal fragment dislocation.

Peleg et al. (2010) intend to examine the performance of a principal strain fixation ratio measure (SR) generated through patient-specific FEA compared with experimentally measured SR values following proximal femur fracture fixation. SR is defined as the ratio of principal strains that develop in a fixated bone relative to the principal strains that develop in the same bone in an intact state. This variable enables the detection of strain shielding and overstrained patterns at the time of fixation; hence it can be an indicator for bone adaptation and failure prediction helping to assist in the selection of fixation alternatives. They conclude that for a given force the FE SR field output variable is less sensitive to changes in density-elasticity relationships and the response function is more accurate than the FE calculated strain values of the fixated model. Moreover, the experimental data confirms the assumption that the SR values are independent of load amplitude.

Wieding et al. (2012) present an approach for automatically modeling screws with structural elements and their fixation with an adequate accuracy on arbitrary FE meshes. Moreover, the method presented is compared to experimental testing and other modeling approaches. Three different modeling techniques for implant fixations are used in the study: without screw modeling, screws as solid elements and screws as structural elements. The accuracy of the FE models is confirmed by experimental tests using a composite femur with a segmental defect and an identical osteosynthesis plate for primary stabilization with titanium screws. For the two screw modeling techniques studied, a sufficient correlation of approximately 95% between numerical and experimental analysis is found. Furthermore, using structural elements for screw modeling the computational time could be reduced by 85% using hexahedral elements instead of tetrahedral elements for femur meshing. The automatically generated screw modeling offers a realistic simulation of the osteosynthesis fixation with screws in the adjacent bone stock. Hsu et al. (2012) use FEA to study the best screw configuration to achieve this goal. The objective is to assure a certain level of stability in the fixation with the minimum number of screws. This topic is currently under debate among specialists. Wongchai (2012) also studies the effect of eight configurations of the screw fixation and Dynamic Compression Plate (DCP) on the inter-fragmentary strain in femur fractures. Thus, the use of FEA and different body loads shows that the relation of the inter-fragmentary strain and screws are polynomial equations. They finally conclude that the inter-fragmentary strain can be decreased by adding the number of screws with the groups of screw configuration.

5.3. Planning evaluation

The simulation of a fracture reduction is sometimes used for planning a later surgery. In these cases, the expert can evaluate the quality of the simulated process by comparing it with the actual intervention performed a posteriori.

In the literature, there are studies that evaluate the simulated process by testing the suitability of its utilization in planning a real fracture reduction. Cimerman and Kristan (2007) have tested an application for planning the reduction of pelvis and acetabular fractures. This application includes tools for visualizing the fracture in 3D and performing the reduction interactively. In addition, the surgeon can select the fixation devices to add during the simulation. This process is evaluated by planning surgery operations and checking if the planned procedure is followed during the actual intervention. Moreover, the number and length of screws inserted during the operation are also analyzed.

Fornaro et al. (2010a) evaluate the usefulness of an interactive tool for planning acetabular fracture reduction. To this end, the tool was used to plan 7 real cases and the proposed plan was compared with the surgery performed later. In addition, the position of the screws and plates was also compared. Acetabular fractures were also planned using the procedure described by Hu et al. (2011). The proposed procedure allows the user to interactively identify and relocate bone fragments. To evaluate the process, authors used the proposed tools to plan 7 clinical cases in which surgery was subsequently performed. In the evaluation step, they checked whether the plan was followed during the actual intervention. In addition, the number of screws and the length of the plates used during the real intervention were compared with respect to those planned. Tomazevic et al. (2010) present a set of interactive tools for identifying articular fractures that can be useful for planning. These tools are evaluated in the planning of real interventions and their utilization is described. Suero et al. (2010) evaluate the use of a software for the reduction of tibial plateau fractures. For that purpose, they evaluate during planning the time required and whether the 3D reduction is successful. Lee et al. (2012) present a planning system for reducing pelvis fractures and positioning fixation devices. As well as the tests performed with synthetic bones, the system is applied to plan a real surgery. During the evaluation the features found by applying the method in specific cases are extracted, considering the time required to complete each step, the results obtained and the level of interaction required by the surgeon. Chen et al. (2014) evaluate a framework for interactively planning humeral shaft fractures in order to determine whether computer assisted preoperative planning improves the clinical outcomes of humeral shaft fractures. They used the intra-class correlation coefficient (ICC) to test for reliability at a desired lower limit and a confidence interval. The intra-observer and inter-observer reliability for the time needed for all variables was high and all the evaluated patients underwent successfully implemented operations.

5.4. Discussion

As commented in Section 3, the virtual reduction of bone fractures requires the generation of 3D models from CT images that represent the fractured bones. These virtual models are usually generated using an MC based approach. Then noise is removed and the models are simplified in most cases. In spite of the fact that these models are complex, no studies have been proposed to evaluate their goodness. On the other hand, there are no standard criteria for evaluating the accuracy of either the fracture reduction composition or the model quality. Different authors have proposed different methods to measure the quality of the fracture reduction obtained, hence the different methods proposed cannot be easily compared. In most cases authors used artificially generated bones to test their proposed techniques. In these cases, the results obtained cannot be compared since they used different bones to perform the tests: corpse bones and artificial bones of different materials. The special features of long bones have also been used to check the accuracy of the virtual reduction. These features enable the comparison between different methods, but this is restricted to long bone fractures. Registration-based methods can use Mean Square Error (MSE) to test the accuracy of the final alignment of the fracture surfaces. This measure can only evaluate this step of the process and is only applicable in methods that use registration techniques.

The stability of fracture reduction has also been measured in recent years. To that end most of the studies used FEA-based methods. In 1972, Brekelmans et al. (1972) pioneered the use of FEM to evaluate the mechanical behavior of skeletal parts. In 1983, Huiskes and Chao (1983) presented a survey detailing the first ten years after the introduction of FEM in this area of research. In this early period, the main advances focused on the method rather than the problem possibly because of the number of unknown aspects in the behavior of our biological system. They differentiate between the validity of the FE model and its accuracy: the former validates the precision of the model with respect to the real structure and must be evaluated by experimental verifications or similar, the latter indicates how close a current solution is to its convergence point, mainly depending on the size of the model. The proposals presented in recent years usually validate the FE model before applying it to the specific problem. With respect to virtual fracture reduction, FEA has been used for various purposes: measuring inter-fragmentary movement, comparing different fixations, checking stress shielding, calculating fixation parameters and analyzing the suitability of different fixation techniques. For a complete planning of the intervention, soft tissues surrounding the bones should be considered including their customized mechanical properties. But, nowadays, this procedure is unviable because of the intrinsic difficulty of obtaining the corresponding patient-specific models from real clinical cases.

In order to evaluate the density of the trabecular tissue, the use of a more accurate image acquisition technique is mandatory. μCT has enabled the evaluation of the density of this type of tissue, but the radiative impact of this kind of technique has already been mentioned. In addition, μCT has been helpful in determining the mechanical stability of bone implant constructs. As we previously mentioned in the discussion of Section 3.4, the development of new high resolution image acquisition techniques that reduce radiation would be desirable.

The next steps should allow an automation of the surgery as has been introduced in other medical disciplines (Jun et al., 2014; Pile and Simaan, 2014). This automation would enable the utilization of computer-guided surgery using robotic systems. In this regard, proposed methods to reduce bone fractures virtually have been applied in the planning of real surgery. Improvement of the currently proposed techniques would ease the development of robotic systems to assist in or even to perform a real fracture reduction. To the best of our knowledge the commercial development is not widespread. TraumaVision (Swemac, 2015) is a virtual simulator that enables the virtual reduction of different fracture cases providing haptic feedback to the specialist. The research of new methods to automate the fracture reduction process and the analysis of its results could contribute to the development and improvement of these types of commercial solutions.

6. Conclusions

Due to the huge complexity of some fractures, computer assisted techniques have been required to ease and provide technological support to the preoperative planning of the fracture reduction process, reducing in this way surgery risk and diminishing recovery time of the patient. In this survey we have reviewed the techniques and approaches proposed to help medical specialists in this virtual process, from the entry of a patient (generation of bones and fragments models) to the analysis of the final composition including fixation devices, if any. The methods have been summarized and classified, and their main advantages and shortcomings have been highlighted and discussed. We have noticed that none of the stages of the virtual reduction process is completely resolved, neither the identification and generation of fragments, nor the fracture reduction itself. As a consequence, this field of research is still open and faces important challenges in a mid-term period.

The identification of bone fragments requires manual user interaction and sometimes expert knowledge. The ideal would be that all the bone fragments were segmented automatically and simple fractures were identified without user intervention. For this purpose, new methods to automatically separate wrongly-joined fragments are needed. The use of more precise medical images, such as μCT, could avoid fragments appearing together in most cases. However, these images are not always available and has an important radiative impact on the patient. After the identification process, the next step consists of placing all the bone fragments in their correct position to obtain the original shape of the bone. In the future, new methods need to be developed to relocate all the fragments properly in all types of bones and fractures and without using any template. The virtual stabilization of a fracture is almost an unexplored research field. New systems that suggest the fixation devices to be used and their position would be very helpful in the preoperative planning of complex fractures. Finally the development of better image acquisition techniques is mandatory in order to test the suitability of the results obtained by the virtual fracture reduction process. All this progress should allow the automation of the process as is happening in other medical disciplines, and the development of more advanced commercial simulators. Ideally, this automation could lead to the development of computer-guided surgery systems using robots.

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