Chapter 2

Bone anatomy, fractures, visualisation and data collection

Bones are organs composed of hard living tissue that perform many functions including structural support. In different parts of the body, bone is organised in different ways, both macroscopically and microscopically. Despite their strength, bone fractures sometimes occur. These fractures need to be accurately diagnosed and treated. However fractures can be missed during reading of x-ray images, creating a need for automated fracture detection methods.

This chapter examines the structure and function of bones and joints, and explains the types and incidence of fractures that occur, as well as how they can be treated. The incidence of missed fractures during interpretation by the radiologist is examined, as are the possible mechanisms by which misses can occur. A solution to the problem of missed fractures is proposed, along with the fractures that were chosen for testing an automated detection system. Finally, information about the x-ray images used for development and testing of the algorithms is given.

2.1   Bone structure and function

The human skeleton (Figure 2.1) is made up of 206 named bones, that account for about 20% of body mass. Bone is a type of hard endoskeletal connective tissue that supports body structures, protects internal organs (such as the brain, spinal cord and
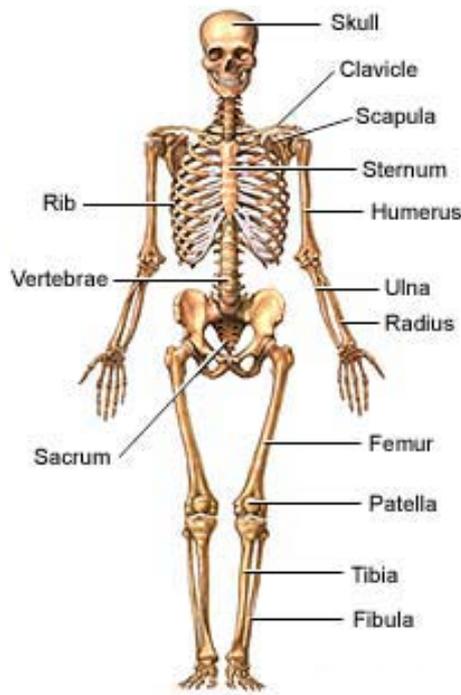
Figure 2.1: The human skeleton. Replicated from Adam Healthcare [2].

thoracic organs), and facilitates movement in conjunction with other tissues (the tendons, ligaments and muscles). Bones are also involved with blood cell formation, calcium metabolism, and mineral (calcium and phosphate) storage.

Bone is a relatively hard and lightweight composite material containing both organic and inorganic components consisting of living cells embedded in a mineralised organic matrix. The organic components include the cells (osteoblasts, osteocytes and osteoclasts) and the osteoid. One third of the matrix is made up of osteoid, which includes the proteoglycans, glycoproteins and the collagen fibres, all of which are created by osteoblasts. The organic components, in particular collagen, are responsible for the flexibility and tensile strength that allow the bone to resist twisting and stretching. Without them, bones would be hard, but extremely brittle.

The inorganic components of bone consist mostly (65% by mass) of calcium phosphate mineral salts chemically arranged as calcium hydroxyapatite. The calcium salts are present as tiny crystals that lie in and around the collagen fibres in the extracellular matrix. These components produce the exceptional hardness of bone, and allow it to resist compression. The proper combination of the organic and inorganic components makes bones exceptionally durable and strong, without being brittle.
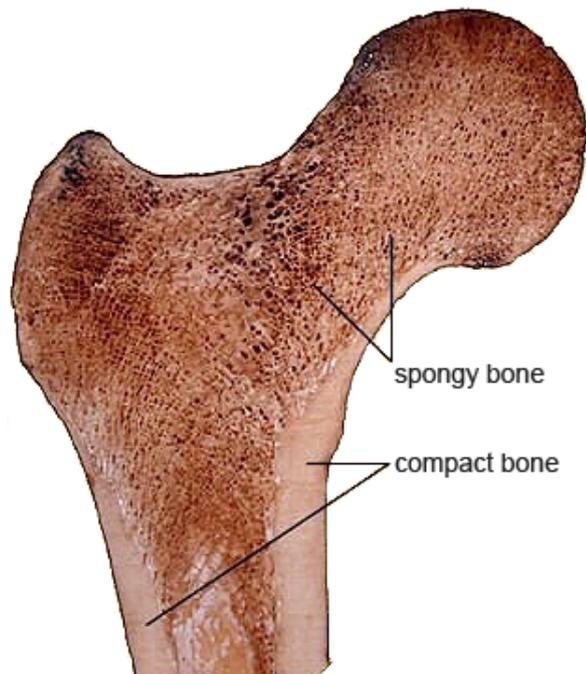
Figure 2.2: Spongy versus compact bone. Adapted from the University of Glasgow Institute of Biomedical and Life Sciences [5].

2.1.1   Types of bone

Classification by structure

Bone has an internal mesh-like structure (Figure 2.2) that varies in density at different points. Bone can be either compact or cancellous (spongy). The outer cortical bone layer is compact, and comprises a substantial portion of skeletal mass (because of its high density) while having a low surface area. Despite its appearance, compact bone also contains many passageways and canals that are conduits for blood vessels, nerves, and lymphatic vessels.

In contrast, cancellous bone is trabecular, and its structure looks like a honeycomb. While appearing to be randomly organised, the trabeculae generally align along lines of repeated stress and help the bone to resist that stress as much as possible. The trabeculae are only a few cell layers thick, so cancellous bone has a relatively high surface area, but forms a smaller portion of the skeletal mass. The open spaces between the network of trabeculae are filled with red bone marrow, which is responsible for blood cell production.
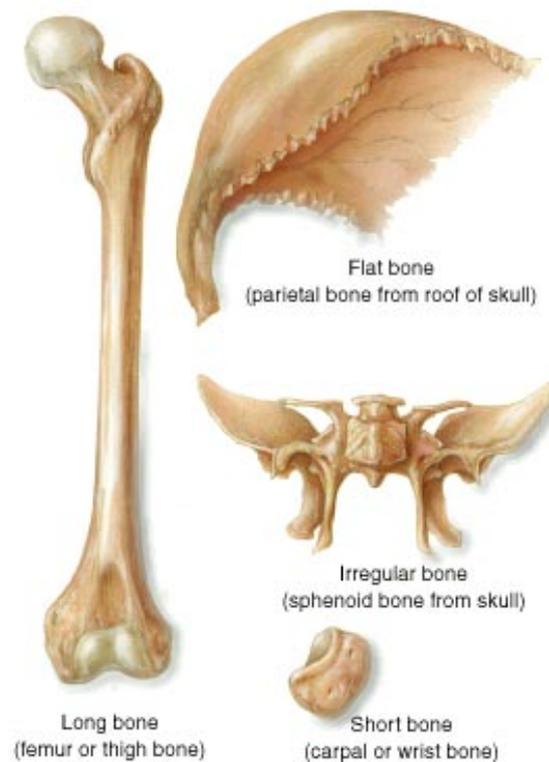
Figure 2.3: Classification of bones based on shape. Replicated from Marieb [67].

Classification by shape

Bones can be classified by their shape as long, short, flat or irregular, as shown in Figure 2.3. The long-bones—such as the femur shown in Figure 2.4—are tubular in structure, and consist of the the following regions:

Diaphysis: The central shaft of the long-bone is called the diaphysis. It is located between both metaphyses, consists of compact bone walls, and has a hollow medullary cavity that is filled with yellow bone marrow in adults, and red bone marrow in children. The external surface of the diaphysis is covered by the periosteum.

Epiphysis: The rounded end or head of a long-bone that consist of mostly cancellous bone covered by a relatively thin layer of cortical compact bone.

Metaphysis: The body of cartilage that separates the epiphysis and the diaphysis. Epiphyseal plates (growth plates, or physes) are located in the metaphyses and are responsible for growth and lengthening of the bone during childhood.

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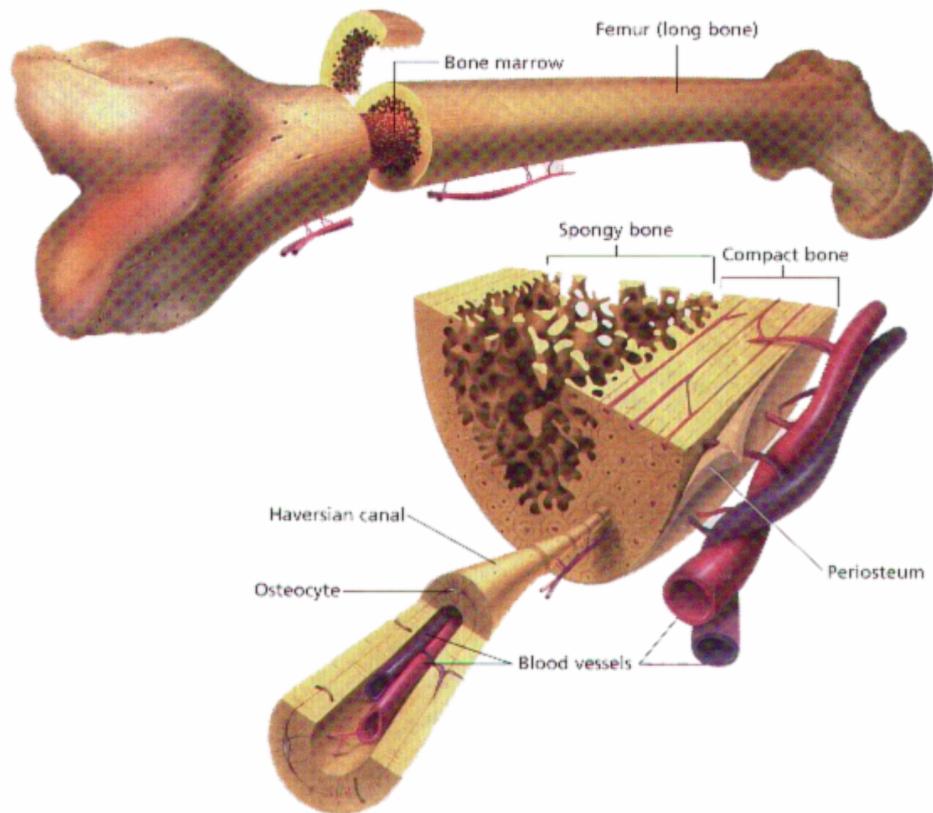
Figure 2.4: The structure of a long-bone. Replicated from Marieb [67].

At roughly 18 to 25 years of age, the metaphysis stops growing altogether and completely ossifies into solid bone.

Diametaphysis: The region between the metaphysis and the diaphysis, where the bone shaft begins to widen and curve.

Short bones—such as the finger bones, wrist and ankle bones, and the patella—have a similar structure to long-bones, except that they have no medullary cavity. The flat bones in the skull and ribs consist of two layers of compact bone with a zone of cancellous bone sandwiched between them. Finally the irregular bones are bones such as the vertebrae and pelvis, which do not fit into any of the previous categories.

2.1.2 Bone remodelling

Despite appearances, bone is a very dynamic and active tissue. Large quantities of bone are constantly being removed and replaced, and bone architecture continually changes, often in response to the mechanical forces placed on it. In an adult, there is a continuous cycle of bone deposit and resorption termed bone remodelling. Bone

resorbing cells called osteoclasts break bone down and discard worn cells. After a few weeks the osteoclasts disappear and osteoblasts come to repair the bone. Bone deposit then occurs where the bone is injured or additional bone strength is required. During this cycle, calcium is deposited and withdrawn from the blood. In a young and healthy adult, the rates of resorption and deposit are equal, so the total bone mass remains constant.

2.2   Joints

Joints are the sites where two bones meet. The two fundamental functions of joints are to provide the skeleton with mobility, and to provide mechanical support. While joints are the weakest part of the skeleton, their structure can resist forces that attempt to move them out of alignment.

Joints can be classified in two ways, either by structure or by function. The functional classification is based on the amount of movement allowed at the joint. Functionally, joints can be classified as synarthroses, amphiarthroses, or diarthroses. Synarthroses are joints that allow no movement, amphiarthroses allow a small amount of movement, while diarthroses allow a variety of movements. The structural classification focuses on the material binding the bones together, as well as the presence or absence of a joint cavity. Structurally, joints can be classified as fibrous, cartilaginous, or synovial. In fibrous joints, such as the cranial sutures, the bones are connected by tight and inflexible layers of dense connective tissue, designed to not allow any movement. Cartilaginous joints, like the pubic symphysis and the growth regions of immature long-bones (the metaphyses), are connected entirely by cartilage and allow only slight movement. Synovial joints are those in which the articulating bones are separated by a fluid-containing joint cavity, and at which movement is possible.

2.2.1   Synovial Joints

Synovial joints are the most common and most moveable joints in the body, and all synovial joints are freely moveable diarthroses. All the joints in the limbs are of this type, as are many others. Synovial joints have five distinguishing features that can be

seen in Figure 2.5:

1. A glassy-smooth articular (hyaline) cartilage that covers the opposing bone surfaces. Articular cartilage is multi-layered, with a thin superficial layer providing a smooth surface for the bones to slide against each other, an intermediate layer responsible for distributing and absorbing compressive loads, and a deep layer to anchor the articular cartilage to the bone.

2. A space between the articulating bones called the synovial cavity.

3. A ligamentous sac called the articular capsule that surrounds the whole joint and covers all internal joint surfaces that are not covered by hyaline cartilage.

4. A small amount of slippery synovial fluid that occupies all the free space within the joint capsule, and provides a slippery weight bearing film that reduces friction between the articular surfaces.

5. Reinforcing ligaments that strengthen the joint. In some cases the ligaments are intrinsic thickenings of the fibrous capsule, while in others they are distinct and lie outside the capsule.

In addition to the five basic components, some synovial joints also contain other structural features. The hip and knee joints contain fatty pads between the joint capsule and the synovial membrane, while others have discs or wedges of fibrocartilage separating the articular surfaces of the bone. These menisci divide the synovial cavity into two parts, and improve the fit between the articulating bone ends, increasing the stability of the joint.

While synovial joints have the common structural features just outlined, they generally do not have a common structural plan. Figure 2.6 shows how synovial joints can also be further grouped based on their shape, and in turn the types of movement they allow:

- Plane joints, such as the carpals of the wrist

- Hinge joints, such as the elbow (between the humerus and ulna)

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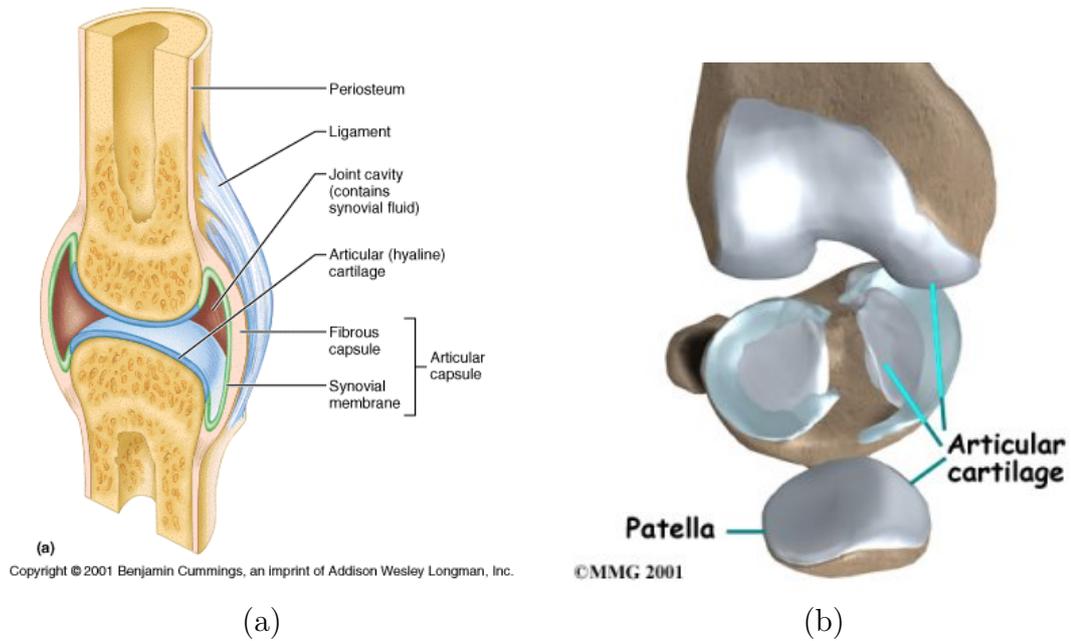
Figure 2.5: (a) The general structure of a synovial joint, and (b) the articular cartilage in the knee, on the distal femur, proximal tibia and the patella. Replicated from Marieb [67] and DePuy Orthopaedics [3], respectively.

- Pivot joints, such as the elbow (between the radius and ulna)

- Condyloid (ellipsoid) joints, such as the knee

- Saddle joints, such as the thumb

- Ball and socket joints, such as the hip and shoulder

2.3 Bone fractures

Although they are very flexible and strong, bones are still susceptible to damage. If more force is put on a bone than it can stand, it will split or break. A break of any size is referred to as a fracture. Most fractures that occur before adulthood result from exceptional trauma such as sporting injuries, falls from a height, car accidents and falls that twist or smash the bones. In addition, repetitive forces such as those caused by running, can cause stress fractures. In old age, fractures can also result from very low applied forces—as the bones become thinner and weaker fractures occur with increased frequency.
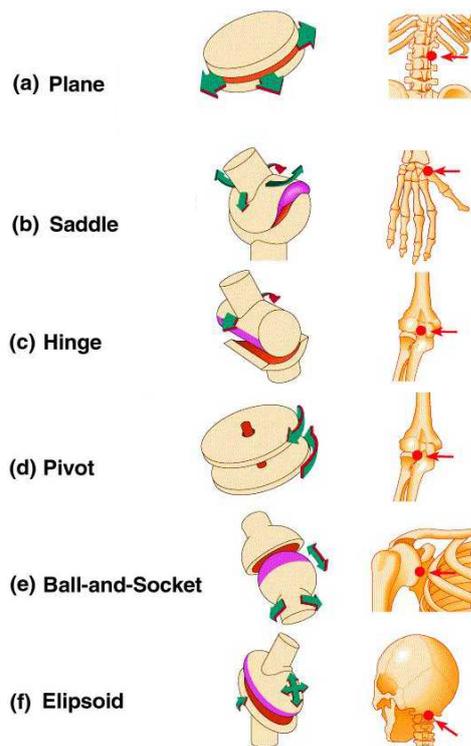
Figure 2.6: The types of synovial joints, including examples of each. Replicated from Wayne State College [7].

2.3.1 Fracture types

Various types of fractures can occur, ranging from very thin hairline fractures to complex fractures consisting of two or more fragments. The common types of fractures are shown in Figure 2.7. In the most basic classification, bone fractures can be categorised as being either simple or multifragmentary (otherwise known as comminuted). The term simple is used to describe a single fracture line through a bone with the broken parts still in their normal anatomical position and minimal damage to surrounding tissue, whereas the term multifragmentary refers to a fracture in which there are two or more bone fragments present. Fractures can also be described as being compound (alternatively referred to as open), or complicated. In a compound fracture, a broken bone protrudes to the exterior of the body through an open wound, giving rise to soft tissue injuries of the muscles, tendons, ligaments, blood vessels and nerves. With compound fractures, there is also a high risk of infection of the internal tissues. A complicated fracture is a fracture of the bone combined with a lesion of an organ, artery, nerve bundle, or joint.

Fractures can also be classified into a number of other categories. A transverse
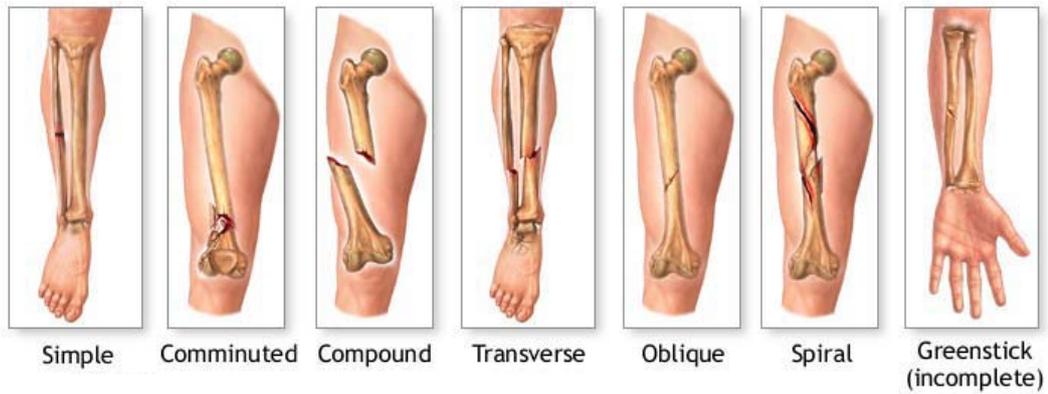
Figure 2.7: Types of long-bone fractures. Replicated from Adam Healthcare [2].

fracture is a break across the bone, at a right angle to the long axis of the bone, and is most often caused by direct traumatic injury. Oblique fractures are one of the rarer types, and are similar to a transverse fracture other than occurring at an angle to the long-bone axis, rather than perpendicular to it. A spiral fracture is a highly unstable fracture that runs around the axis of the bone, and indicates that the break is the result of a twisting motion. On an x-ray, a spiral fracture has a corkscrew like appearance, and without the correct x-ray view it can be incorrectly diagnosed as an oblique fracture. A greenstick fracture is an incomplete fracture in which only one side of the bone is broken. Commonly seen in children because their bones contain more collagen than adults, and therefore tend to splinter rather than break completely, this type of fracture is caused by bending with the break occurring on the outside of the bend. Greenstick fractures are considered to be stable because the bone is not completely broken, and generally heal quickly provided the bone is immobilised.

Insufficiency fractures are an additional type of fracture that includes stress fractures and osteporotic fractures. A stress fracture is an overuse injury caused by repeated or prolonged forces against the bone, causing a hairline crack to form. These fractures result from repetitive subthreshold loading that, over time, exceeds the bone's intrinsic ability to repair itself. Stress fractures are most commonly seen in the lower limbs as a result of the ground-reaction forces that must be dissipated during running, walking, marching, or jumping. Stress fractures of the upper limbs, ribs, and even the scapula have also been described and are not uncommon in some sports.

A common cause of fractures in the elderly is osteoporosis, a group of diseases
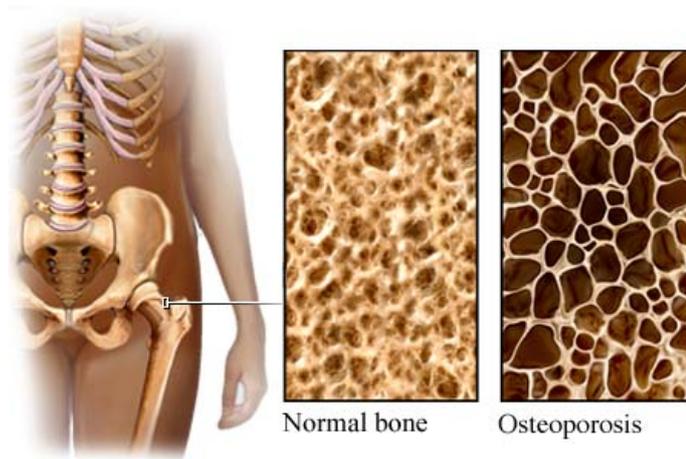
Figure 2.8: A comparison between normal and osteoporotic bone reveals that the trabeculae are thinner and therefore weaker. Replicated from WebMD[6].

in which bone resorption occurs faster than bone deposit. The composition of the bone matrix remains unchanged, but the bone mass is reduced, so that the bones become more porous and lighter (Figure 2.8). Although osteoporosis affects the entire skeleton, the spongy bone in the vertebrae, neck of femur, and wrist is most susceptible to fracture. The condition leads to increased bone fragility and higher risk of fracture, and if left untreated the disease can progress painlessly until a bone breaks with minimal trauma.

2.3.2 Fracture incidence

Fractures of bone are a common affliction, accounting for approximately 20% occupancy of orthopaedic wards at any given time [30]. It was estimated that in 1992 the annual treatment costs in Australia for atraumatic fractures occurring in people older than 60 years of age was $A779 million [86]. In the Australian population, the number of fractures associated with age-related bone loss is increasing rapidly, with the number of non-hip fractures estimated to increase by 9% every 5 years until 2036 [94], primarily due to the ageing population. Worldwide, women have a 30–40% lifetime risk of suffering an osteoporotic fracture, while men have a lower risk of 13% [59]. Approximately 6.8 million Americans break a bone each year. On average, every person in the United States will experience two broken bones over the course of their lifetime.

2.3.3   Fracture diagnosis

In order to effectively treat a fracture, it is necessary to determine if, where and how the bone is broken. There are a number of symptoms of a broken bone, including:

- A visibly out-of-place or misshapen limb or joint

- Swelling, bruising, bleeding or hematomas

- Intense pain

- Numbness and tingling

- Broken skin with bone protruding

- Limited mobility or inability to move a limb

- Skin stretch marks or band marks

In addition to these symptoms, palpation (feeling for broken bone ends) and auscultation (listening for crepitus) can also be used to determine the presence of a fracture. However, medical imaging is the best method available for confirming the presence of a fracture. Although today there are many imaging modalities available to examine anatomic structure—such as computed tomography (CT), magnetic resonance imaging (MRI) and ultrasound (US)—the majority of fractures are diagnosed with plain diagnostic x-ray images. In the case of most simple fractures, the clinician requests a series of these images, centred on the area in which the symptoms indicate that a fracture is most likely.

The images are produced by placing an x-ray film or other detector on one side of the injured limb, and an x-ray source on the other (Figure 2.9). During the exposure, the x-rays are absorbed most heavily by dense material such as bone, and to a much lower extent by less dense tissues such as muscle and fat. The resulting image is light[1] in the bony areas where the x-rays were absorbed (and the film is not exposed as much) and dark in the soft tissue areas where the x-rays were not absorbed [46].

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[1]As noted at the beginning of this thesis, the contrast of the x-ray images in this document is inverted, so that they are clearer on paper.

Figure 2.9: X-ray images are acquired by placing the injured region of the patient between an x-ray source and a photosensitive film. Dense structures such as bone cause that part of the film to be less exposed than others, creating a clear image of the anatomy. Replicated from Adam Healthcare [2].

The image produced is therefore a projection of a three-dimensional structure onto a two-dimensional plane, so that all structures in the path of the beam overlap on the resulting image. As a result, some structures can be hidden by this overlapping, so x-rays are generally taken at a number of orientations. Naturally, other structures in the path of the x-ray beam influence the image that is produced, and often also complicate the problem of fracture detection. Once a sufficient number of views of the fractured bone are obtained, the images are analysed by a radiologist, to determine if the bone is indeed fractured, and if so then in what location and in what manner.

A radiology student or inexperienced observer will not learn very much from a patient film without some kind of systematic instruction in basic viewing problems [100]. Therefore they must first be taught how to examine a film. This involves obtaining some basic understanding of why x-ray shadows appear as they do, as well as being familiar with a minimum normal range for the shadows that are seen. They also require the ability to visualise the three-dimensional patient while viewing a two-dimensional film. A radiology student should be able to recognise the most frequently encountered abnormal appearances, and then relate them logically to gross pathology. To determine if a bone is fractured, an experienced radiologist examines the x-ray image in the same way. The summation of shadows is analysed to visualise the corresponding three-dimensional structure, and this in turn is classed as either within or outside the normal range [100].

2.3.4 Fracture classification

Following radiographic confirmation of the fracture, its location, nature and severity must be determined as a basis for treatment [75]. That is, the injury to the bone must be recognised, identified and described [32]. This requires inspection of the radiographic image and classification of the fracture in accordance with an established scheme. Fracture classification schemes are anatomic location specific, and therefore hard to directly compare. Some of the most common ones are:

- The AO[2] classification [75]

- The Salter-Harris classification [92]

- The Gustilo open fracture classification [44]

The AO long-bone fracture classification scheme

In the internationally accepted AO fracture classification scheme, the clinician is required to classify the fracture based on both its location and its morphological characteristics. The location is designated by two numbers, shown in Figure 2.10, that indicate in which bone and which segment of the bone the fracture is located. The bones are numbered:

1. humerus

2. radius and ulna

3. femur

4. tibia and fibula

while the segments are numbered:

1. proximal

2. diaphyseal

3. distal
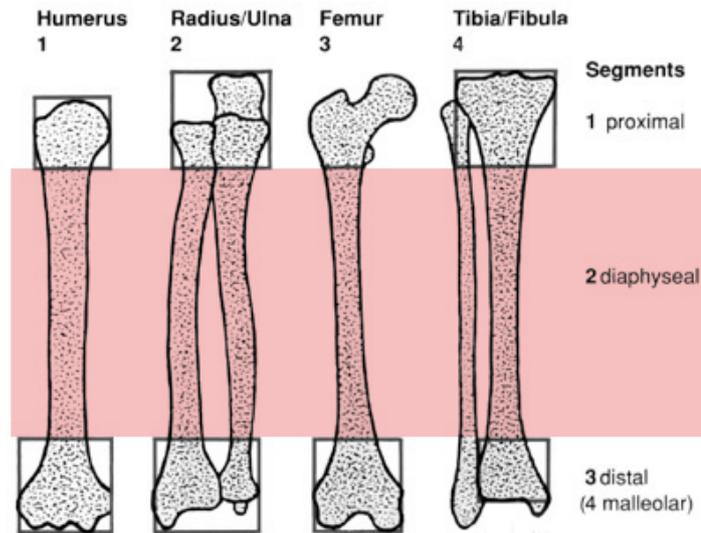
Figure 2.10: The fracture location is designated by two numbers. The first (horizontally) of these indicates which bone, while the second (vertically) indicates which segment. Adapted from Muller [75].

4. malleolar

After the location is coded, the fracture is classified into one of three types shown in Figure 2.11. The meaning of the type varies depending on the location of the fracture. For example, a midshaft fracture would be assigned type A for a simple fracture, type B for a wedge fracture, and type C for a complex fracture. On the other hand a distal long-bone fracture would be assigned type A for an extra-articular fracture, type B for a partial articular fracture, and type C for a complete articular fracture. The fracture is then divided into three groups and three subgroups, which again vary depending on the fracture location. The result (shown in Figure 2.12) places the fracture into one of twenty-seven possible classifications, each with a unique coding, varying in severity in accordance with morphologic complexity. This classification is used as a guide to prognosis and the most effective treatment. The AO scheme is recommended because it is clinically relevant, simple, reproducible and provides a good estimate of the clinical outcome [75].

The Salter-Harris classification scheme

The Salter-Harris classification scheme (Figure 2.13) is used only used for paediatric fractures that involve the growth plate (metaphysis). These types of injuries account for

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[2]AO—Association for the Study of Internal Fixation
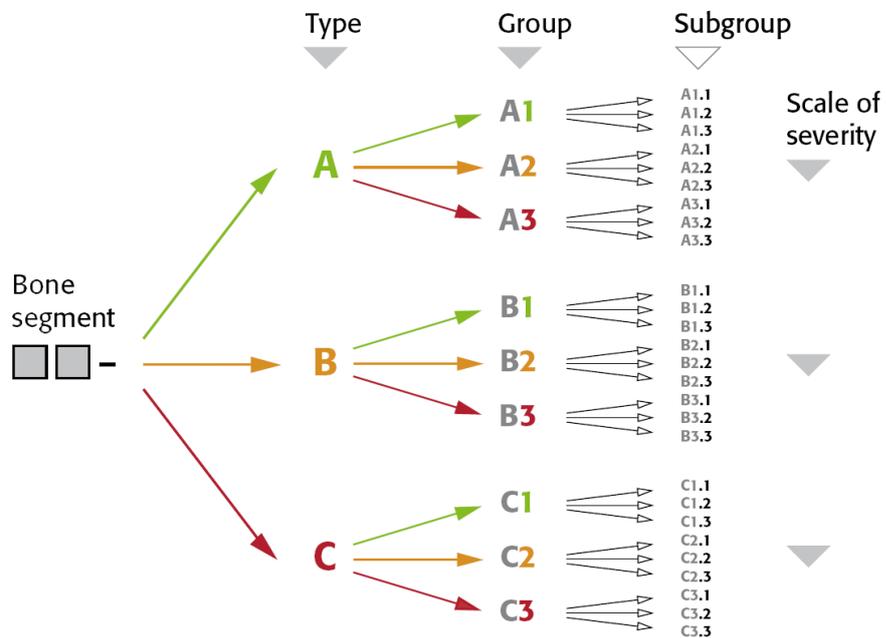
Figure 2.11: The AO classification scheme assigns the fracture to one of 27 possible combinations of type, group and subgroup. Replicated from Muller [75].
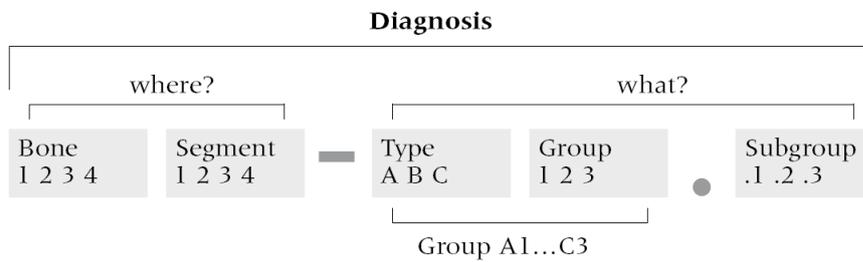
Figure 2.12: The alpha-numeric coding of the classified diagnosis. Replicated from Muller [75].
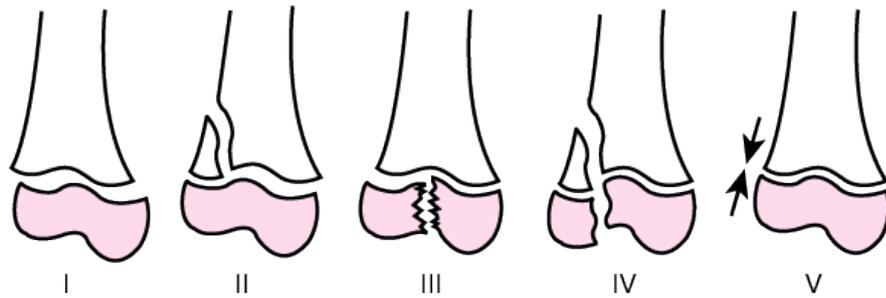
Figure 2.13: The Salter-Harris classification scheme. Replicated from the Medical Journal of Australia [4].

15–20% of major long-bone fractures and 34% of hand fractures in childhood. The large majority of these fractures heal without any impairment of the growth mechanism but some lead to clinically important shortening and angulation. Growth plate fractures may lead to growth disorders due to destruction of epiphyseal circulation, thereby inhibiting physeal growth, or by allowing a bone bridge to form across the growth plate. In the Salter-Harris classification scheme fractures are categorised as one of five types:

I   Fracture across the physis with no metaphysial or epiphyseal injury

II   Fracture across the physis which extends into the metaphysis

III   Fracture across the physis which extends into the epiphysis

IV   Fracture through the metaphysis, physis and epiphysis

V   Crush injury to the physis

The Gustilo open fracture classification

The Gustilo open fracture classification is used for compound fractures, that is those in which the skin has been disrupted. This classification describes the soft tissue injury, but does not necessarily describe the fracture severity. There are three major grades that attempt to quantify the amount of soft tissue damage that is associated with the fracture. The grades take into account the wound size, the amount of crushing, and the level of contamination:

1   The wound is less that 1cm with minimal soft tissue damage, and is un-
         contaminated.

2   The wound is greater than 1cm with moderate soft tissue injury, the wound
         bed is moderately contaminated (or the fracture contains moderate com-
         minution).

3   The wound is greater than 10cm with crushed tissue and contamination.

Type 3 injuries are typically the result of trauma from farmyard injuries, high velocity
gun shot wounds or the crushing force from a fast moving vehicle. They can be fur-
ther categorised by whether soft tissue coverage of the bone is possible, soft tissue is
inadequate and requires a free flap, or whether there is also a major vascular injury re-
quiring repair for limb salvage. Type 3 fractures can also be further classified using the
mangled extremity severity score [52], predictive salvage index [48], limb salvage index
[90] or the nerve, ischemia, soft tissue injury, shock, and age score. Based on these
classifications it is sometimes necessary to consider below knee amputation following
tibial fracture.

Other fracture classification schemes

There are many other location specific classifications. For example, fractures of the
pelvis can be classified using the Pennel and Sutherland classification, fractures of the
clavicle with the Allman / Neer classification, and fractures of the tibial plateau with
the Schatzker classification. These classifications are only relevant to their particular
anatomical region, and so cannot be directly compared.

2.3.5   Fracture treatment

Bone fractures heal naturally through a physiological process, provided they are suffi-
ciently immobilised. Insufficient immobilisation can result in inadequate healing of the
bone, and the formation of a pseudoarthrosis (or non-union). Accordingly, the three
main treatment options for aiding bone fracture repair all involve immobilising the
fractured bone pieces. For simple fractures, the most common and sufficient method is
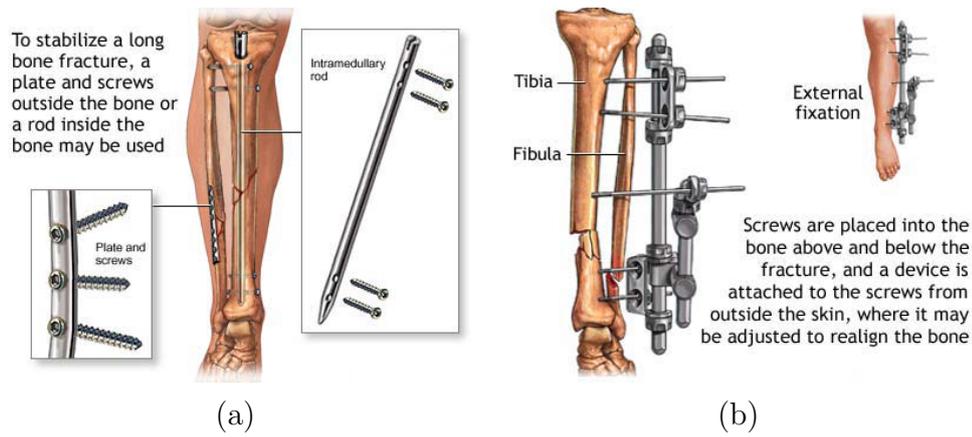
Figure 2.14: Fracture immobilisation by (a) internal fixation, and (b) external fixation. Replicated from Adam Healthcare [2].

closed reduction under anaesthetic, followed by the application of a plaster cast around the exterior of the limb. For more severe fractures open reduction and internal fixation (Figure 2.14a) is used. This technique involves surgery to apply metal rods, screws or plates that remain in place under the skin after the surgery, to allow the bone to heal. This procedure is recommended for complicated fractures not able to be realigned (reduced) by casting, or in cases in which the long-term use of a cast is undesirable. Finally, open reduction and external fixation (Figure 2.14b) involves surgery to repair the fracture, and placement of an external fixation device on the limb with the fracture. This device is an external frame which supports the bones and holds them in the correct position while they are healing. This technique is generally applied to complex fractures that cannot be repaired using open reduction and internal fixation.

2.4 Missed diagnosis

2.4.1 Incidence of missed fractures during reporting

It is estimated that every year in the USA, one in five radiologists is sued for malpractice [18]. It was reported by Berlin [20] that of these suits, the largest category involves missed radiologic diagnosis (40%), and within this group the most common type are missed fractures (also 40%). A miss is defined as either failure to see a significant finding, or attaching the incorrect significance to a finding that is readily seen. A more recent study of 5497 radiologists from 42 US states by Baker and Harkisoon [16] showed

that 51% had reported at least one instance of a medical malpractice suit. Of those suits, 45% involved a failure to diagnose, and the leading cause of those were missed fractures at 29%.

Trained radiologists generally identify abnormal pathologies including fractures with a relatively high level of accuracy. However studies examining reader accuracy [93, 21, 20] have shown that in some cases the miss rate can be as high as 30%, or even higher when reading x-rays containing multiple abnormalities. Accurate diagnosis of fractures is vital to the effective management of patient injuries. While litigation costs are an expensive problem, of more importance is the ineffective patient management and prolonged treatment time that results from missed fracture diagnoses.

2.4.2 Why fractures are missed

When examining x-rays of a patient with multiple injuries, obvious lesions can overshadow more subtle ones, producing a significant possibility that some will be overlooked [17]. A psychological mechanism known as satisfaction of search (SOS) has been suggested as a possible source of error during the reading of these types of x-rays [93]. The detection of one abnormality can interfere with the detection of other abnormalities in two ways. Firstly, any detected abnormalities distract the observer from identifying other abnormalities, and secondly the detection of an abnormality causes the search to halt prematurely. The magnitude of the SOS effect is also influenced by the severity of the distracting abnormality [17]. As a result, identification of a severe fracture in one location detracts from the detection of a subtle fracture in another location.

Injuries can also be missed because a second fracture is a long distance from an obvious one. For example, a non-displaced fracture of the scaphoid may be overlooked in the presence of an obvious fracture of the radius and ulna [88], or an injury to a proximal joint can be overlooked in the presence of a shaft fracture of a long-bone (i. e. fracture of femur and dislocation of the hip). This leads to a phenomenon known as the edge of x-ray diagnosis, in which an x-ray is centred on one abnormality, and there is a second abnormality that is either very close to the edge, or even partly over the

edge of the x-ray image. As in the satisfaction of search mechanism, the abnormality is missed, in this case because it is not in the centre of the reader's field of view.

Other studies [88] have also shown that there are a number of injuries that are commonly missed, especially due to the lack of compliance in unconscious patients. Interpretations with localisation clues have been shown to be significantly more accurate than interpretations without such clues [18]. It has been suggested that the patient's clinical history (for example the trauma mechanism or the presence of localised pain, tenderness or swelling) may prompt the observer to extract a particular type of information from multiple anatomic regions [18]. In addition, these clues improve the ability of orthopaedic surgeons to detect fractures in a trauma patient even more than they improve the ability of radiologists [19]. If these clues are not present because the patient is unconscious, then it is possible that the interpretation will be less accurate.

2.5 The proposed solution to prevent missed diagnoses

The high rate of missed fractures identified in Section 2.4.1, and the increasing incidence of fractures among the population, suggests that a method of increasing vigilance for unexpected abnormalities is required to help prevent missed fractures [93]. In addition, the number of medical imaging studies, number of images per study [11], and number of modalities commonly used are all increasing, creating an information overload that demands development of automated fracture detection methods [28].

The increasing availability of radiographic images in digital form suggests a digital image processing approach could lead to more reliable diagnosis and treatment of fractures. The aim of this research was to create a computer algorithm that could consistently segment an area of interest, as well as detect and highlight fractures within the segmented region. An automated CAD scheme that searches the entire field of view without being distracted by an abnormality or terminating when an abnormality is detected, as well as weighting all regions of the image with appropriate importance (edges of the image as well as the centre), could help reduce the number of fractures

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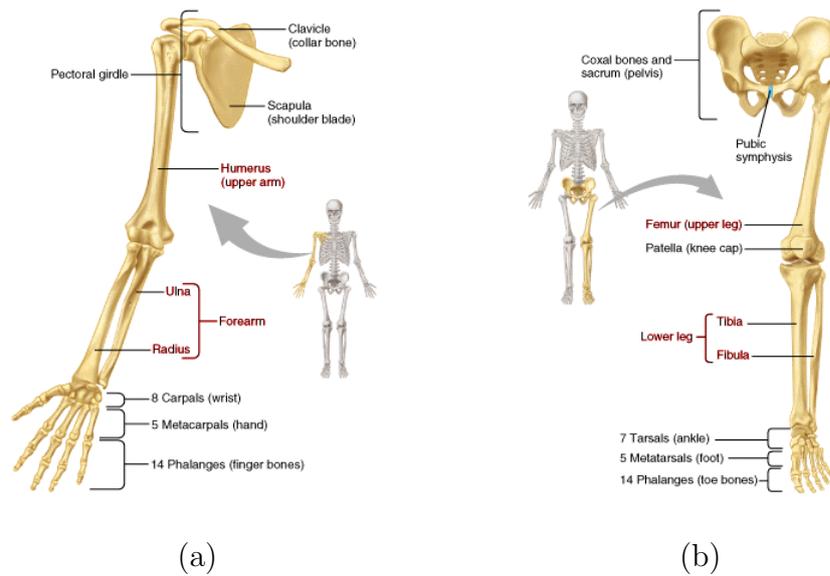
Figure 2.15: (a) The upper extremities, including the humerus and radius / ulna, and (b) the lower extremities, including the femur and tibia / fibula. Replicated from Marieb [67].

that are missed during the reading process. In addition, this system could also be used to help less trained people than radiologists—such as doctors working in disaster areas—to make diagnoses without a radiologist being present.

2.5.1 The fractures chosen for automated detection

As previously mentioned in Section 2.1.1, bone structure varies depending on anatomic location, with trabeculae present at the proximal and distal ends of the long-bones, and only thick cortical bone in the shaft. Unlike fractures of the epiphyses, fractures of the diaphysis (Figure 2.10 in red) are not easily hidden by the trabecular texture. Although proximal and distal fractures account for a large proportion of all limb fractures, automating their detection was not considered at this stage. Some fractures of the diaphyseal segment are easier to detect than fractures in other parts of the body, however their accurate detection is still a very difficult, important, and unsolved problem. For this reason, midshaft long-bone fractures were chosen for the initial testing of a fracture detection scheme. Figure 2.15 shows the proximal and distal long-bones in the upper and lower body.

According to the AO group, the boundary between the proximal and distal segments is defined as being perpendicular to the centre-line of the long-bone, at a distance from the articular surface that is equal to the widest part of the epiphysis [89]. When these

boundaries are located at each end of the bone, the diaphysis is defined as the region in between. Figure 2.10 shows the squares used to create bounding boxes over the joints of each long-bone, to calculate the location of the diaphyseal boundaries. One limitation of this method is that it requires an anteroposterior (AP) x-ray of the long-bone, rather than a mediolateral (ML) x-ray, because the epiphyseal width cannot be determined from a mediolateral image.

2.6 Image data collection

To test any computer algorithms written to detect fractures in an x-ray image, it is necessary to have an appropriate series of test images. Discussion with radiologists and Emergency Department physicians revealed that the majority of long-bone fractures are diagnosed using anteroposterior and lateromedial standard diagnostic x-rays, as described in Section 2.3.3. Exceptions to this included intra-articular fractures, or complex fractures involving other structures such as major arteries and vessels. It is only in these less common situations that three-dimensional imaging techniques such as CT and MRI are used. Consequently a long-bone fracture detection scheme should ideally be based on two-dimensional, rather than volumetric data. A set of plain diagnostic test radiographs therefore needed to be acquired.

Initial collection was undertaken in Adelaide, at the film libraries at the Flinders Medical Centre (FMC), Women's and Children's Hospital (WCH) and the Medical Radiations Department at the University of South Australia (UniSA). These libraries are used for teaching and reference purposes, and contain x-rays of interest from many teaching hospitals around the world. Although a large number of x-rays containing fractures were collected from these sites, preliminary studies showed that many were not suitable for the task of automatic fracture detection. Most images were very old, often dating back to the early 1970s, and were taken using much less advanced x-ray equipment. Consequently the image quality and resolution were much lower, and abnormalities were much harder to detect, even in the hands of an experienced diagnostic radiologist. It was also found that any new x-rays added to film library collections were often copies of the original image, and were of much lower quality than

the originals.

The preliminary studies concluded that high quality x-rays were required in order to detect fractures within long-bones. In order to obtain high quality images of midshaft long-bone fractures, new digital or hard copy x-rays needed to be obtained because they had the potential for better image quality [82]. New x-rays are less likely to suffer from the low resolution and artifact that may be present due to age, equipment quality and x-ray film damage. High quality digital x-rays which were ideal for the task of fracture detection were hard to obtain, because in 2002 there were few locations in South Australia that had digital x-ray equipment and complete picture archiving and communications systems (PACS) installed. In addition, at the commencement of the study, there were no known libraries of suitable, high quality, high resolution, digital x-rays available in Australia. However the Emergency Department at the FMC uses a mini-PACS[3] digital system to retain images for a fortnight before printing and archiving the images in hard copy format. Ethics approval was sought from the FMC Clinical Research and Ethics Committee for short-term prospective access to de-identified x-ray images of human long-bone fractures, for the development and testing of the fracture detection algorithm.

In 2003, a database containing fractures of long-bones was created using x-rays from patients examined at the Flinders Medical Centre. Images of normal, intact long-bones were also included in the data set, as were any available images of contralateral limbs. The accuracy and reliability with which the fracture detection algorithm makes a dichotomous decision about whether or not a bone is fractured could therefore be determined. For each case in the image library, the actual x-ray image, the patient age and gender, the x-ray scanning parameters and any diagnosis were recorded. Personal information (patient name and hospital ID) was not included in the library, to ensure patient anonymity and confidentiality. Over a period of 25 months, 115 images were collected from 54 patients. Some statistics about the images in the complete image library are shown in Figure 2.16.

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[3]An incompletely implemented PACS system. In this case long-term storage of x-rays is not yet in a digital format.
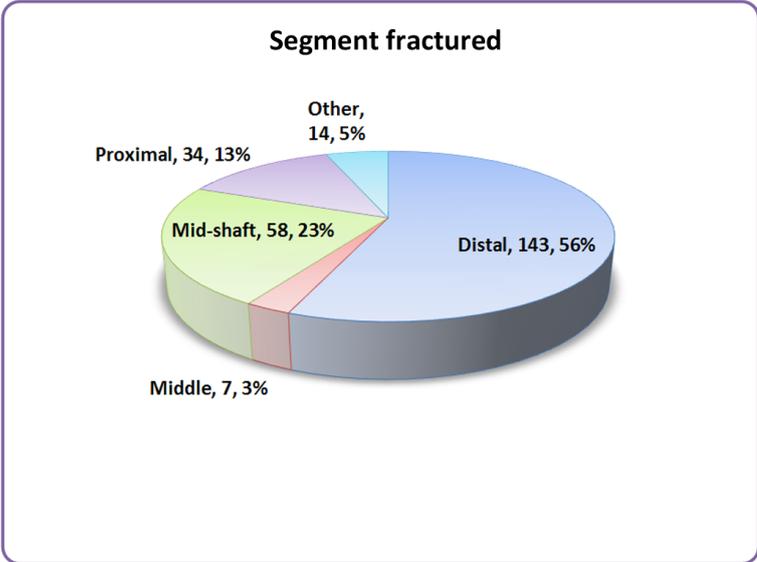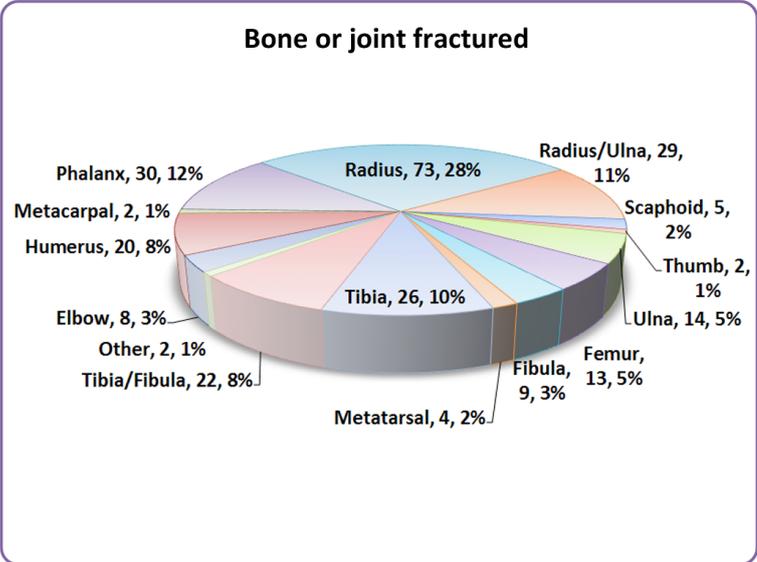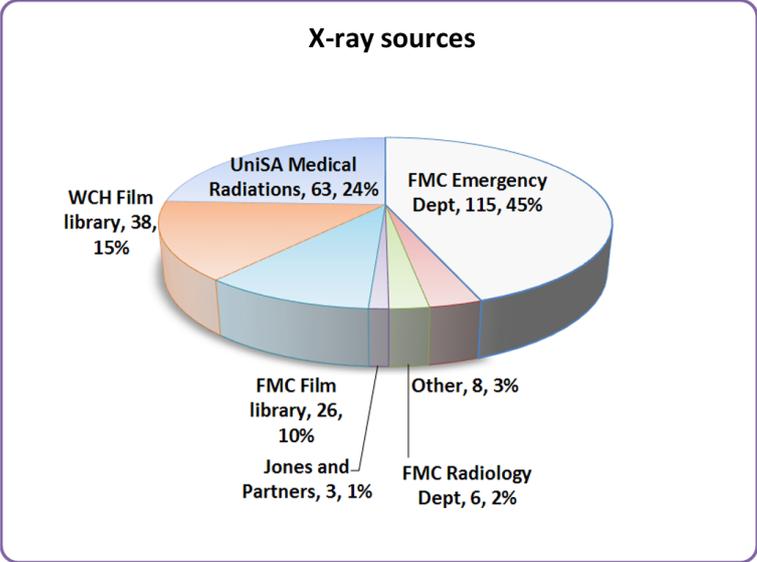
Figure 2.16: X-ray image database information.

2.6.1 Image digitisation

Digital Imaging and Communications in Medicine (DICOM) is a standard for storing, handling and transmitting information in medical imaging. DICOM was developed to allow integration of medical imaging scanners, servers and workstations from multiple manufacturers into a PACS. The DICOM files consist of a header containing metadata consisting of standardised and free-form fields, as well as a body of image data. This information could include the study date and time, modality, equipment manufacturer, hospital, study description, anatomical location, image size and bit depth. A single DICOM file can contain any number of images, so that all patient information is grouped together into a single data set. This means that all information about the patient is stored under a single patient ID, so that an image is never mistakenly separated.

Ideally, the raw DICOM data would be directly obtained from the PACS computer after the patient is scanned. However in the FMC system there was no means by which this data could be accessed. Since the digital data could not be accessed directly, the only acceptable solution was to print the images to high quality x-ray film in the Emergency Department. These x-rays were then digitised with high fidelity using a high quality A3 Umax Powerlook 2100XL x-ray scanning system in the Imaging Laboratory in the Department of Surgery, Orthopaedic Unit at the Repatriation General Hospital in Daw Park, SA. The images were all scanned at a resolution of 3600 x 1200 pixels (approximately 600 pixels per inch) at a depth of 8-bits/pixel gray scale, which is higher than the parameters published by other groups researching algorithms for the analysis of x-ray images [39]. Incidentally, this aspect ratio $(3:1)$ was chosen because it was found to be suitable for imaging long-bones, since they are much longer than they are wide, and it also minimises the amount of blank space around the bone. After scanning, the images were written to DVD in Tagged Image File Format (TIFF), with no compression.

2.6.2 The image development and test sets

Unfortunately, many of the images collected from the film libraries, and in some rarer cases the FMC Emergency Department, were not suitable for testing the algorithms

described in this thesis. This was due to a number of reasons, such as the images:

- being of low quality as a result of outdated x-ray technology, deterioration with age and previous handling, and scratching over time.

- containing artifacts that occurred during acquisition or printing.

- containing foreign objects (such as clothing, casts, intravenous lines, artificial joints and external fixators) that would mislead the algorithms.

- simply not showing the appropriate anatomical region.

As a result, the complete set of images was cut down to two sets, one that could be used for algorithm development, and another that could be used for algorithm testing. The image sets used for development and testing were not chosen completely randomly. Not only was it important that the images showed the correct anatomic location, but a mix of upper and lower extremities, proximal and distal locations, and images of varying complexity, were all required. Images that satisfied these criteria were manually selected from the complete set, to give a good representation of the images likely to be seen in an emergency department.

The development set was comprised of 6 images from 6 patients (2 male, 2 female, 2 unspecified), ranging in age from 7 to 18 ($\overline{x} = 12$, $\sigma = 5.35$). Examination by a radiologist showed that five of the images contained at least one fracture (2 contained two fractures), while one contained no fractures. The test set consisted of 44 images from 31 patients (20 male, 11 female), ranging in age from 5 to 88 ($\overline{x} = 34.2$, $\sigma = 28.6$). Examination by a radiologist showed that 38 of the 44 images contained at least one fracture (9 contained two), and 6 contained no fractures. The locations of all the identified fractures were recorded so that the performance of the fracture detection algorithm could be compared to a human observer. Information about all three image sets (complete, development and test) is displayed in Table 2.1.

| | | Image Set | | |
		Complete	Development	Test
	FMC Emergency Dept	115	4	44
	Other	8	0	0
	FMC Radiology Dept	6	0	0
Source	Jones and Partners	3	0	0
	FMC Film library	26	0	0
	WCH Film library	38	1	0
	UniSA Medical Radiations	63	1	0
	Upper Extremities	183	3	26
Region	Lower Extremities	74	3	18
	Other	2	0	0
	Elbow	8	0	0
	Humerus	20	1	2
	Metacarpal	2	0	0
	Phalanx	30	0	0
	Radius	73	0	13
	Radius/Ulna	29	1	11
	Scaphoid	5	0	0
Bone/Joint	Thumb	2	0	0
	Ulna	14	1	0
	Femur	13	1	3
	Fibula	9	0	2
	Metatarsal	4	0	0
	Tibia	26	2	8
	Tibia/Fibula	22	0	5
	Other	2	0	0
	AP	160	5	29
View	LAT	92	1	15
	AP/LAT	7	0	0
	Min Age	1	7	5
	Max Age	88	18	88
	Mean Age	34.30	12.00	34.26
Patient Statistics	Age Standard Deviation	29.92	5.35	28.65
	Number of Males	35	2	20
	Number of Females	20	2	11
	Number with sex unknown	11	2	0
Total		259	6	44

Table 2.1: *Information about the complete, development and test image sets. Note that in all cases other than the patient statistics, the numbers refer to the number of images of each type, so patients with multiple images are included. For the patient statistics, the numbers refer to the number of patients, so that patients with multiple images are only counted once.*

2.7 Summary

Bones are complicated and dynamic tissues that are responsible for support, protection, movement and blood cell formation. The structure and function of bone varies depending on anatomic location, and includes two types of bone—cortical and trabecular. Despite their flexibility and strength, bones can be fractured when too large a force is applied, and various types of fractures can occur depending on the mechanism of the injury. After diagnosis, fractures are normally classified using one of a number of classification systems to determine both the severity and the most effective treatment plan. Unfortunately in some cases fractures are missed during diagnosis, resulting in ineffective patient management and increased treatment time. The SOS mechanism and edge of x-ray diagnosis were suggested to be likely sources of this error.

To reduce the high rate of missed fractures, a digital image processing approach to the problem of fracture detection was proposed. The problem was simplified by examining a small subset of fractures, those that occur in the long-bones of the upper and lower limbs. To design and test algorithms, a set of plain diagnostic x-ray test images was compiled from three teaching film libraries in South Australia. The images obtained were generally of insufficient quality, so an additional set of images was acquired from the Emergency Department at the Flinders Medical Centre. All images were digitised using a high quality x-ray scanning system. Of this complete set of images, a test set of 44 images was created for testing purposes and a development set of six images was created for algorithm design purposes.

The next chapter overviews the related work that has been performed on both computer aided detection of fractures, and automatic image segmentation for medical images. It also formally states the aims of this thesis.