INVESTIGATION INTO THE USE OF
THE ILIZAROV FRAME FOR THE
CORRECTION OF CONGENITAL
TALIPES EQUINOVARUS
(Clubfoot)

A thesis submitted to the University of Manchester for the degree of

Doctor of Philosophy (PhD)

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ABSTRACT

Name of University: The University of Manchester
Submitted by: Gerardo Hernandez Hernandez
Degree title: Doctor of Philosophy
Thesis title: Investigation into the Use of the Ilizarov Frame for the Correction of Congenital Talipes Equinovarus (clubfoot)
Date: December 2015

Clubfoot is one of the most common pathologies of the foot affecting 1 in 1000 newborn babies according to statistics. The first treatment approach is by using conventional procedures, such as plaster and cast, and, the literature reports a range of failures causing relapse. Patients with severe or relapsed cases or patients that are treated later in life may require unconventional procedures to provide correction. In order to increase the success rate after the correction, it is necessary to: a) to perform analyses to improve the current treatments and, b) investigate the tissues involved in this pathology in order to have a better understanding of clubfoot to develop future treatments. The Ilizarov fixator has been shown to be a good alternative for complex and relapsed cases. However, there are no numerical nor experimental studies to: a) improve the efficiency of the frame deployment for clubfoot, b) provide guidance on the right adjustment procedures, and c) understand the mechanical behaviour of the frame applied to clubfoot. This makes the adjustments fully dependent on the surgeon’s experience instead of systematic guidelines/procedures. This results in configurations that induce stresses in the fixator that are transferred to the tissues and leading to a reduction in the success rate. Furthermore, the literature on the correction of clubfoot in babies and the role of the tissues in babies’ feet during the correction is limited.

Therefore, the aim of the thesis is to analyse the relationship between the adjustments of the connectors and the displacements of the fixator rods, on the one hand, and the stress-strain induced in the rods and fixator, on the other hand. This is achieved by means of a finite element analysis of the stress-strain distributions in the fixator components. The predicted stresses are used for the identification of the components that should be adjusted in the fixator to prevent them from failure. The findings and results in the thesis will enable surgeons to understand better the mechanical behaviour of the Ilizarov frame in clubfoot, and they will facilitate the establishment of a functional range of the fixator in order to improve the current procedures. Another aim is to investigate the mechanical behaviour of one of the most affected bones during the correction of clubfoot in babies, namely the talus. The literature reports a change of shape in the talus during clubfoot correction using conventional procedures. This can result in a change of the stress distribution in the foot tissues during gait in latter stages of life leading to different pathologies. This clearly shows the importance of investigating the mechanical behaviour of the talus. This is the first numerical study to investigate the right adjustment procedures of the frame for clubfoot. It is expected that the findings of this research contribute to the improvement of the current corrective procedures based on the use of the Ilizarov frame and to improve the understanding of clubfoot in babies.
NOMENCLATURE

\( \mu_w \)  Linear Attenuation Coefficient

\( A \)  Area (mm\(^2\))

\( A \)  Attenuation Coefficient

\( E \)  Modulus of elasticity or Young’s modulus (MPa)

\( E_{CT} \)  CT Scanner Transmitted Energy

\( E_{CT} \)  Young Modulus (Confined Talus) (MPa)

\( E_{\text{Talus}} \)  Young Modulus (Talus from CT scans) (MPa)

\( \gamma \)  Activation Function

\( \gamma \)  Transfer Function

\( \text{HU} \)  Hounsfield units (HU)

\( I \)  X-Ray intensity

\( I_0 \)  Intensity of a CT scan beam

\( N_0 \)  initial Intensity produced by the CT scanner

\( N_i \)  Intensity of the transmitted X-Ray

\( N_f \)  Intensity of the Transmitted X-Ray

\( U \)  Poisson’s ratio

\( V_0 \)  Initial Volume (mm\(^3\))

\( U_{CT} \)  Poisson’s Ratio (Confined Talus)

\( V_f \)  Final Volume (mm\(^3\))

\( U_{\text{Talus}} \)  Poisson’s Ratio (Talus from CT scans)

\( W_{jn} \)  Synaptic Weight for Artificial Neural Networks

\( X_n \)  Neural Network Inputs

\( Y_j \)  Sum of Signals (ANN)
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DECLARATION

I hereby declare that no portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Gerardo Hernandez Hernandez

2015
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1.1 Background

The foot is part of the lower limb of the human body which performs the movement and gait by means of different tissues such as bones, tendons, ligaments and muscles, functioning as a single part. Its complexity, because of the huge amount of soft tissues surrounding 26 bones, makes the foot difficult to be modelled and studied. The optimal function of the foot, in concomitance with the ankle, is highly relevant to guarantee a proper gait and avoiding pathologies such as ankle arthrodesis, fractures and else in adulthood and old age. The reason is that this limb bears the body weight (Riegger, 1988; Rodgers, 1988) and provides stability to the entire body when walking or standing up. Also, any problem associated with the foot and ankle caused by an improper gait can be reflected in other upper limbs such as Knees, hip or spine. In the case of clubfeet, the bones are inwards, and it causes an irregular gait when the proper treatment is not provided (Jain et al., 2009).

Clubfoot, also called talipes equinovarus (Wiliams, 1968; Shelton & Banton, 2009; Swamy et al., 2009), is a very common congenital pathology of the foot and ankle (Pagnotta et al., 1996; Dobbs et al., 2000; Jackson & Stricker, 2003; Regondi et al., 2012), which treatment and correction are complicated (Ponseti, 1992). The reason is that the foot and ankle in clubfeet display four principal deformities, equinus, varus, adductus and cavus (Muñoz, 2006). In normal feet, the angle between the Calcaneus and Talus is 40° compared to a smaller angle in clubfeet. In addition, four main criteria can distinguish a normal foot from another affected by any pathology: 1) the ability to walk, 2) the absence of pain when walking 3) the absence of malformations and 4) the absence of deformities. In the case of clubfoot the statistics show a high prevalence in the population, about one to three in a thousand people depending on the country (Tillett et al., 2000; Ballantyne & Macnicol, 2002; Siapkara & Duncan, 2007; Macnicol & Murray, 2008; Swamy et al., 2009). The statistics on clubfoot and the significance of the
right gait to efficiently perform everyday tasks or those in sports emphasize the importance of investigating the aetiology, the assessment or the procedures to correct clubfoot and other pathologies in the foot and ankle.

In the case of clubfoot, invasive (operative) and non-invasive corrective procedures have been referred and documented in the literature (Kite, 1939; Fripp & Singer, 1953; Turco, 1971; Kite, 1972; Ilizarov, 1987; Ponseti, 1992; Dimeglio et al., 1996; Dobbs et al., 2000; Parigi, 2004; Singh & Vaishnavi, 2005; Bronfen et al., 2009). Non-operative methods have been previously suggested as the first treatment option (Kite, 1972; Sud et al., 2008). The is because, it is important to consider a reduced rate of side effects or pain during the treatment, as in general, surgical procedures can cause various complications in patients. Moreover, it is essential to guarantee reliable end results comparable to normal feet. In general terms, non-invasive methods are the first option when the deformity is considered not severe, or it is assessed just after birth, while some surgical or invasive procedures are the most common choice for relapsed or severe cases. However; many of these aspects still need to be intensely studied to determine the proper treatment in function of the severity, pain or expected outcomes. Therefore, results after the various procedures diverge among methods according to the literature (Richards et al., 2008; Sud et al., 2008).

Ponsetti and Ilizarov’s techniques are two well-known procedures for clubfoot correction. The former is often proposed as a non-invasive method in newborn babies, and the latter is commonly used to correct relapsed and severe clubfeet when conventional treatments have failed. In cases where gradual changes of the limb position are necessary, Ilizarov technique is an appropriate choice. This is because it usually do not cause severe complications compared to other methods, for instance, osteotomies or triple arthrodesis (Prem et al., 2007). Furthermore, the Ilizarov technique can be applied to patients of different ages, starting from childhood or even in newborn babies. As well, the technique is an adequate option to treat clubfoot in adults where, soft tissues are stiffer than in children. This method consists on placing a frame around the foot and ankle with tensioned wires to connect the limb to the frame. Subsequent adjustments are required during the treatment in order to correct the deformity. Although, general procedures are described in the medical literature, there is not an existing validated method to determine the frame’s adjustment directions and their right
adjustment frequency. Also, elements of the frame such as rods, or rings become bended or broken after being used by patients, resulting in malfunctioning of the frame. So that, it currently depends on to the experience of the surgeon in charge (Chotel et al., 2002), and it results in some cases on poor results after correction (Franke et al., 1990).

1.2 Aims and objectives

The principal aims of the thesis are to investigate the mechanical behaviour of the Ilizarov frame used for clubfoot correction in order to optimize the frame deployment. In addition, to study the effects of the compression of the talus, that has been reported to be one of the most affected bones of the foot during clubfoot correction. The objectives of the thesis are listed as follows:

- To develop solid models of the foot and ankle using CT scans
- To perform Finite Element analyses of the Ilizarov fixator.
- To create a novel 3D model of the talus of a baby based on CT scans.
- To analyse the effects of different compression levels on the Talus of newborn babies with clubfoot
- To create a novel 3D model of the Ilizarov Fixator assembly applied to clubfoot correction.
- To identify the highly stressed areas caused by the displacement of single main rods during the correction
- To test the advantages/disadvantages the use of Artificial Neural Networks as a technique to increase the reliability of the mesh analysis.

1.3 Scope of the thesis

The foot and ankle are part of the most complex limbs to be analysed in the human body due to its high amount of soft tissues in comparison to other human limbs. At present, there are some numerical models on the foot and ankle in normal feet. More complex
models of the foot have been developed during the time by different authors. Experimental tests on the foot tissues have been reported in the literature to analyse the mechanical properties of the ligaments and bones in normal feet but, there are no studies on the mechanical properties of the soft tissues in clubfoot conditions neither in babies nor adults. It is very important to determine novel methods to assess the severity of clubfoot. On the other hand, there are studies on the analysis of some of the Ilizarov fixator elements and the assemblies for tibia and fibula corrections but there are few numerical models on the applications to lower limbs for deformity correction. One of the most complex deformities to analyse is clubfoot because it considers four deformities to be corrected namely, cavus, varus, equinus and adductus. Therefore, the contributions to the clubfoot corrections by the use of the Ilizarov frame can be extended to other deformities in the lower limb. In the present thesis, the development of the Ilizarov frame geometries and assembly applied to clubfoot correction has been developed. Finite Element Analyses of the Ilizarov fixator assembly for clubfoot corrections to identify the highly stressed areas by individual rods displacements were performed. It contributes to understand better the behaviour of the Ilizarov frame when performing further more complex adjustments during the correction process. This will provide guidance to surgeons about the connectors and frame elements to be adjusted when applying displacements on the correcting rods. Also, this contributes considerably to the understanding of the proper deployment of the frame to achieve the best possible results during the correction.

On the other hand, the mechanical properties of the foot tissues depend on many factors. One of them is the age of the patients. The talus is one of the most affected bones by different corrective procedures. In addition, the first path to correct clubfoot is commonly determined at the first six months of life. This highlights the importance of understanding the behaviour of tissues in babies. However, the literature on the analysis of tissues in babies and children is limited. Brand et al. (2006), state that particular corrective procedures cause plastic deformations in the talus due to the correction of clubfoot. There is not validated literature on the application of the Ilizarov frame in babies. However, it is important to understand the mechanical behaviour of the bones in babies in order to determine if this procedure is appropriate. A contribution of the current thesis is to investigate the mechanical behaviour of the talus based on the
mechanical properties of babies. Results from this analysis and future studies can lead to
the establishment of corrections in different corrective procedures for clubfoot in order
to reduce plastic deformations in the bones due to the correction. This is the first time
that the role of the tissues in babies is considered in a numerical model, focused on the
analysis of clubfoot.

There are not previous numerical analyses on the Ilizarov assemblies applied to
clubfoot. Every surgeon modifies the frame according to their experience and the
pathology. There are no numerical or experimental studies on the different assemblies.

1.4 Contributions to the Knowledge

Contributions can be summarised as follows:

- Development of the 3D model of the Ilizarov frame applied to clubfoot. This
  enables to analyse the highly stressed areas on the frame due to the rods
  adjustment.
- Identification of the highly stress areas and associated connectors in the Ilizarov
  framer applied to clubfoot as a result of rods displacement.
- Very few analyses have studied the tissues of babies. The current model of the
  analysis of the talus of babies, contributes do investigate the mechanical
  behaviour if that tissues in order to establish safer corrective procedures.
- Identification of the best algorithm to train ANN with a mesh analysis database.
- Comparison and estimation of the yield strength of the frame by displacing four
  independent rods. This enables to analyse and improve the current corrective
  procedures for clubfoot, using the Ilizarov technique.
- There are very few studies on the mechanical properties of babies; the current
  analysis contributes to the understanding of the behaviour of tissues in babies.
1.5 Thesis outline

In this thesis, different aspects of the clubfoot correction by the Ilizarov method were investigated as described in the objectives. There is enough information in the literature about this pathology from the clinical perspective. However, there are few experimental and numerical studies describing the causes of failure of the Ilizarov procedure in clubfoot. In addition, most of the studies have analysed the use of the Ilizarov procedure in limbs lengthening but there is a lack of understanding about: a) the procedure in clubfoot by the Ilizarov technique far away from the general clinical directions, b) the behaviour of the tissues in babies compared to those in adults with clubfoot c) The differences in the directions for adults, kids and babies and d) The Analysis of the frame assembly for clubfoot correction. As an interdisciplinary research involving medical and mechanical aspects, the study of clubfoot in this thesis required different analysis stages. Some studies were covered by the objectives of the current thesis and some of them are considered for future works in a research line of study as described in the last chapter of this thesis. This is because the Ilizarov technique is considered in clinical applications by surgeons as a good alternative for relapsed and severe cases; the right understanding of the procedures and directions of the technique result relevant.

The current thesis outline has the following order:

**Chapter 2** describes the principles of the foot anatomy, necessary to understand the differences between a normal foot and a clubfoot. As well, in this Chapter, there is a basic description of other common pathologies of the foot. The objective of this description is to clarify the difference with other deformities as clubfoot includes four of them, and sometimes similar pathologies may be confused with clubfoot. Secondly, there is a review of essential terms to provide a better understanding of the game language used in: a) medicine, b) engineering, c) this thesis. Finally, clubfoot pathology, assessment procedures, statistics on clubfoot and the most common procedures to correct it are described in this Chapter with the objective of visualising the differences of the most common procedures to correct clubfoot and the differences with the Ilizarov technique, analysed in this work.
Chapter 3 comprises the general description of the Ilizarov method for the clubfoot treatment. Firstly, this Chapter summarises the most relevant applications of the Ilizarov technique, the medical considerations for its application and the historical background on the modern fixators. This provides an understanding of this technique as well as its reaches and limitations. Secondly, the Chapter summarises the literature review on the Ilizarov fixator modelling and related experimental and numerical studies. Finally, the current Chapter contains the literature review of the numerical, and experimental of: a) foot and ankle bones b) soft tissues of the foot. This Chapter has the specific objective of reporting the background studies up to date that provide information for the current analyses performed in this thesis.

Chapter 4 contains the general description of the procedures to create the 3D geometries for the modelling of the foot-ankle bones and the frame. These sections of this Chapter provide a detailed description of the image processing of CT scans images, the verification of redundancies in the geometries to avoid errors in the modelling, the files extensions and the generation of solid geometries imported to Abaqus software (6.10 to 6.13).

The sections of this Chapter firstly contains the description of the operating principles of a CT scanner in order to understand the process to achieve the images used to create 3D models of the foot, used in further chapters. The chapter also contains the description of the full procedures to generate the babies’ foot model, used in Chapter five and also, it describes the procedures to create the Ilizarov frame parts, assembly and model used in the analyses reported in Chapter six.

Chapter 5 describes the analysis of the Talus in babies which is one of the most affected bones during clubfoot correction. In addition, because there are few studies to analyse the mechanical properties of tissues in babies and this is a boundary to perform further numerical analysis in tissues of babies. The Chapter starts explaining the importance of the analysis on the talus of babies and subsequently, describing the methodology for the analysis. The implementation of Artificial Neural Networks (ANN) was performed using the Mesh analysis database as deeply described in section 5.4. Also, basic concepts related to ANN were presented in this Chapter. Also, a FE compression analysis of a confined talus was performed in order to compare data from
the literature with those obtained in this study by FEM. Finally, the Chapter contains a section of discussion and conclusion related to the Chapter.

**Chapter 6** consists of the analysis of the Ilizarov frame applied to the clubfoot correction. This Chapter describes the methodology of the 3D numerical model of the Ilizarov frame to investigate the effects of the displacement of independent rods to identify the highly stressed areas resulting from those adjustments. As a result, the connectors, associated to the adjustment of single independent rods, lead to provide the first numerical model to investigate the behaviour of the frame to contribute to the improvement of the corrective clubfoot procedures. Results, analyses, discussions of the methodology and further future works are described in this Chapter.

**Chapter 7** contains the discussion, mentioning the advantages and disadvantages, the gaps and limitations as well as the clinical relevance. Also, the Chapter includes the conclusions of the thesis as well as advice for future works, based on the analyses presented in this thesis.
Chapter 2 Anatomy, pathologies and clubfoot treatments

2.1 Introduction

The Ilizarov method consists of the use of different mechanical parts to assemble an external fixator around the limb to be treated, then applying subsequent adjustments to correct a particular pathology. In the case of clubfoot, the limb is the foot and ankle. A literature review of the fundamental principles of the anatomy of the foot and ankle provides a better understanding of the variables to establish the conditions for the numerical models of further Chapters. Also, clubfoot involves four different deformities in a single pathology. These are cavus, varus, adductus and equinus. The discussion of those and other most common pathologies is necessary to distinguish the relationship with clubfoot, as well as their main differences. Firstly, in this Chapter, there is a fundamental review of the basic concepts. The objective of that review is to provide a clearer understanding of confusing terms required in this Chapter as well as defining the terminologies used for this thesis. Finally, the literature review examines the biomechanics of the foot, the assessment methods and the different treatments for clubfoot, which results in identifying the differences among procedures with the Ilizarov method. Also, that leads to understand the importance of analysing this particular method to provide correction for Congenital Talipes Equinovarus or clubfoot instead of other procedures.

2.2 Basic concepts

Wittgenstein described the importance of language to communicate ideas and concepts efficiently. He assigned the term “language games” to the particular group of terms
shared by a group of people to represent those ideas and concepts (Wittgenstein & Anscombe, 1967). The current thesis covers multidisciplinary topics from engineering and medicine. Thus, as part of this Ph.D. thesis, the objective is clearly not to focus on a broad discussion of those concepts and terms but to provide a brief explanation of some confusing terms. Finally, this section contributes to defining the “language game” for this thesis and describing some important concepts related to the anatomy and biomechanics of the foot and ankle.

Firstly, when distinguishing any pathology in the foot from the average, standard or healthy foot, it is common to describe it as a “normal foot”. However, the term normal can be vague as it comes from the Latin normalis and norma meaning “into the rule” and “in the norm “. This definition avoids those pathologies in which geometry and integrity of the tissues are “into the norm” but, because of minor differences can present, for example, pain or promoting degenerative illnesses such as cartilage attrition.

From a functional perspective, a normal and healthy foot meets the following criteria: 1) allows walking, 2) is painless, 3) does not present deformities, 4) does not have malformations in the tissues. In addition, a “normal foot” inversion angles must be between 4 to 6 and 6 to 7 for eversion (Hamill & Knutzen, 1995). In plantar flexion, the angles are 115 degrees between the tibia and talus, as higher values are associated with the equinus foot (Kirienko et al., 2003). Also, the Dimeglio scale is issued for clubfoot assessment where, twenty is a severe clubfoot and zero is a normal foot. It helps to determine a normal foot from the perspective of assessment procedures. Those criteria are sufficient to distinguish a “normal foot” from pathologies.

On the other hand, the term “healthy”, from the Latin salus, salutaris and salvus (intact and entire), in comparison to the term “Normal”, does not compromise the “norm” but its integrity. Perhaps, it is a better alternative to use the terms, "normal and healthy foot" to describe the foot defined in the previous paragraph. Other terms such as standard or average foot could be another option to describe a “normal and healthy foot”. However, in this thesis, the term Normal is mostly used to avoid confusions, as many authors make use of this single term (Irani & Sherman, 1963; Waisbrod & Tiberias, 1973; Dimeglio et al., 1995; Wedge et al., 2001; Butcher & Atkins, 2003; Kirienko et al., 2003).
Other common terms described in this thesis are “Clubfoot” and “Congenital Talipes Equinovarus”. They are commonly understood to be the same (Pagnotta et al., 1996; Shelton & Banton, 2009). Clubfoot is defined by (Ponseti, 1992; Jackson & Stricker, 2003; Muñoz, 2006), in terms of four components of the deformity: cavus, adductus, equinus and varus. One or other of these two terms is used in different countries of the world. In the USA, it is relatively more common to use the expression “talipes” due to the etymology from Latin where, in contrast with the word “clubfoot”, talus means “ankle” and pes means “foot”. The term, clubfoot is more frequently employed in the United Kingdom due to its resemblance to a golf club. On the other hand, the meaning of “talipes” should be considered as a condition of the foot where it keeps the integrity of all its elements but, because of external forces, its shape has been modified (Browne, 1959). Even if this pathology has been associated with some of the different foot deformities, in the USA, clubfoot is defined as “Congenital Talipes Equinovarus”. The term equinus has been used to describe the equinus deformity because it is similar in appearance to the horse’s foot, and the term varus describes the orientation of the foot.

Some articles describe the term idiopathic when referring to clubfoot (Dobbs et al., 2000; Dobbs & Gurnett, 2009). It is a usual term in medicine to define an affliction whose causes are unknown, or the aetiology is dim. The etymology of these terms comes from the Greek word “idios” which means one’s and “pathos” that means suffering. Due to those origins of the concepts, it is common to describe clubfoot as an idiopathic disorder. In most of the writing of this thesis, the term clubfoot will be mainly used, but as well it is described as talipes equinovarus as a synonym.

Another term, when talking about the Ilizarov procedure, is the word frame, which is applied to name the device for the clubfoot treatment. This is because, once it is placed on the foot and during the correction, it works as a closed structure. It is regularly used in the literature as the Ilizarov frame or the Ilizarov fixator, so both terms are employed in this thesis to describe the same device.

On the other hand, aetiology, which is understood as the causes and origins of pathologies or illnesses, is commonly written as “etiology” and “aetiology”. Both are correct, and their application depends on the region of the world; it is broadly written as “aetiology” in the UK. Other terms, namely: deformity and malformation can cause confusion. Malformations are produced in the embryonic period while deformities in the
2.3 Anatomy of the foot and ankle

The lower limb, which compromises the foot and ankle, has a significant role in the optimal biomechanical performance of the human body. The foot contains 26 bones from a total of 206 bones of the entire human skeleton in adults. In addition, it has 33 joints and many soft tissues (ligaments, tendons, muscles, cartilages) surrounding the foot and ankle to provide it with stability and allowing the movement of the body (locomotion). This complexity makes it difficult to formulate methods to analyse the real foot under normal conditions and even more in specific pathologies. However, technologies such as CT scans and MRI scans, using image processing software, are enabling it to be possible.

The foot and ankle are part of the lower limb, the most vital limb of the human anatomy when any task involves the displacement of the body. This makes it necessary to understand the behaviour of the lower limbs during and after correcting any associated pathology. The foot and ankle bear from one to four times the body weight. This is because any activity in a close chain, (when the foot is in contact and interacting with the reacting forces of the ground), from walking upstairs, to running or jumping in sports, demanding different loading conditions. In order to accomplish their functions, the foot and ankle require bones and soft tissues such as ligaments, cartilages, tendons or muscles, to be stiffer, bigger and more in number than those in upper limbs. Particularly, in the case of some sports, for example, football, the optimal function of the foot and ankle is essential to achieve the best possible performance. In daily life, it is difficult to perceive the importance of the lower limb as humans perform various activities perceived to be normal until related foot-ankle pathologies are developed. In old age, pathologies associated with the limb, such as arthrodesis, attrition, bones deviations and fractures due to osteoporosis, can results in total ankle replacements or other surgical procedures, affecting normal life. On the other hand, an improper gait caused by any foot and ankle pathology results in future pathologies in the upper limbs such as the knee, hip or the spine. Moreover, pain and difficulty to perform activities are
other complications. In the case of clubfoot or Congenital Talipes Equinovarus, the main concern is that it restricts to a limited, difficult and painful walking. Those reasons have encouraged the development of different treatments to correct, assess and understand the aetiology of this specific pathology.

The study of the anatomy of the lower limb (foot and ankle) is crucial to develop treatments and assessment procedures. Also, a proper understanding of any pathology in the lower limb, compared to the right function in a normal one, contributes to develop an appropriate methodology to analyse the limb and related pathologies. For those reasons, the literature on the bones and principal soft tissues (ligaments, tendons, cartilages and muscles) is reviewed in further sections of this Chapter, for a better understanding of clubfoot and highlighting the anatomy. The mechanical properties of the foot tissues are described in Chapter 3. In the current Chapter, there is an emphasis on the pathologies, the anatomy of the foot and ankle, the corrective procedures and their relation with a) clubfoot and b) the Ilizarov technique.

### 2.3.1 Bones

Bones are one of the stiffest tissues in the human body. They contain collagen that provides them with enough flexibility necessary to absorb impacts and calcium which gives them enough stiffness. Metabolic functions take place in the interior of the bone. Hence, there are two different classes of bones: compact and spongy. The former is a hard and dense structure which usually joins the muscles and the latter is cancellous and has the function of producing blood cells in the interior such as marrow. The mechanical properties of bones, compared to conventional materials, depend on many variables as any other living tissue. Some of the most relevant are: 1) the limb 2) the patient’s age, 3) nutrition, 4) loading conditions during the lifetime due to different activities, 5) pathologies affecting the bone such as osteoporosis, arthritis and others. Figure 2.1 shows the three sections (tarsals, metatarsals and phalanges) of bones of the foot from two perspectives: the superior and inferior view. The latter view shows the bones in the plantar fascia while the former shows the bones in contact with the tibia and fibula to form the ankle joint.
The foot has 26 bones organised in phalanges, metatarsus and tarsus. The fibula and tibia are linked to the foot by soft tissues. Tarsus has seven bones: three cuneiforms, astragalus or commonly named talus, navicular, cuboid and calcaneus. The last one is located in the anterior end of the foot and below the talus and it is the biggest bone of the foot. The talus is in contact with the tibia and fibula which directly forms the ankle joint by means of ligaments, tendons and muscles. In front of the talus is located the navicular, cuboid and the rest are three cuneiforms as shown in Figure 2.2. The Achilles tendon is joined to this segment of bones in the tarsus, mainly in the talus and calcaneus, as well as calf muscles.
Metatarsus of the foot are organised in 5 bones. The largest one is the first metatarsal because it has the capacity of bearing and distributing the weight of the body and additional forces, such as impacts produced when running or jumping. They are close to the cuneiforms and cuboid in their back side, showing head, base and shaft. In their frontal face, they are joined to the phalanges.

The last section of bones in the foot is the phalanges that comprise 14 bones that form the toes. The great toe has the important function of providing support and stability to the limb to achieve a normal human gait. The other four phalanges have proximal, middle and distal rows of bones.
The tibia is the biggest bone below the knee; it joins its distal end to the talus and forms the ankle joint. The proximal end of the tibia has contact with the femur in the intercondylar eminence. In the distal end, it has a notch which is in contact with the fibula as shown in Figure 2.3.

The fibula is a narrow bone which has the function of joining the muscles more than supporting the weight. Its head on its proximal end articulates with the tibia. The middle of this bone seems to be twisted, and its composition is rigid and heavy. These two bones, in conjunction with the foot bones, form the foot and ankle. They are surrounded by an enormous amount of soft tissues to increase the stiffness of the limb.
In general, the primary functions of bones are:

• Providing Support. In the lower limb, bones bear the weight of the body as a dead load, in addition, to live loads such as those in common activities. Any alteration in the foot and ankle can be reflected in the upper limbs as well as modifying the human gait, resulting in damage.

• Protection. It occurs when bones cover soft organs of the body in order to protect them from impact and to keep them intact. Some examples of their protective function are the skull and ribs. In the foot and ankle, no vital organs need to be protected.

• Gait. It involves the interaction with other tissues such as ligaments, tendons, muscles and cartilages to enable movement and displacement of the body. The geometrical organisation among bones in the limbs modifies the right function of a limb. In the case of clubfoot, the positions of the bones modify the gait, making it difficult to achieve stability, support and movement, causing pain.

• Blood cell formation. It happens inside the cavities of the bones to cover some vital functions, for example, a) providing nutrients to the bones and b) enabling the healing processes after fractures.

2.3.2 Arches of the foot

The arches of the foot have the function of providing stability when walking, and distributing the loads along the foot in a standing position and during the gait phases. An abnormal arch is related to pathologies such as pes-cavus or pes-planus and can result in calluses or fractures due to an improper load distribution in the foot. The soft tissues surrounding the bones of the foot help to reduce the impact when performing activities. There are two kinds or arches: longitudinal and transverse. The former is supported by the calcaneus, three metatarsal bones in the medial part and calcaneus, the cuboid and the fifth and fourth metatarsal in the inner side. The latter, is the transverse arch which is formed by the distal part of the calcaneus, a portion of 5 metatarsal bones, cuboid and navicular (Rogers & Jacob, 1992; Palastanga et al., 2006). In the case of
clubfoot, the arches tend to be higher. This gives to clubfoot the component of pes-cavus. Figure 2.4 briefly summarises the arches of the foot.

![Figure 2.4 Arches of the foot (Marieb, 2004)](image)

### 2.3.3 Cartilages

Cartilages are essential tissues for the human development. They have an important role in the movement and flexibility of the body. The main function of cartilages is to enable the transmission of loads in the joints by providing a lubricated and smooth surface for reducing impact and friction (Fox et al., 2009). Cartilages are located between bones, and like bones, ligaments and muscles, cartilages become stiffer with age. Also, the amount of cartilages in the body reduces with age and is substituted by other tissues, mainly bones.

There are three kinds of cartilage tissues: **hyaline, elastic and fibrocartilages**. The first category, **hyaline**, has the function of providing flexibility and elasticity to the body joints. Also, this is the primary type of cartilage tissues in the foot. Hyaline cartilages are identified as “articular cartilages” due to their composition and functions.
Figure 2.5 shows a scheme of the articular cartilage in a joint. It is visible that the cartilage is located at the top and bottom edges of the bone. The synovial membrane contains the synovial fluid that lubricates the joint. The typical thickness of the articular cartilage in adults ranges between 2 to 4mm and it is mainly composed of collagen, water and proteoglycans, where water and collagen are the most abundant, (Fox et al., 2009). On the other hand, articular cartilage is considered as a viscoelastic material that shows a time-dependent behaviour during constant loading conditions (Fox et al., 2009).

A confined compression test is the common method to evaluate the mechanical properties of cartilages where a sample disc is cut and loaded (Mansour, 2003). This is important for the analyses of Chapter 5 on the talus of babies due to the similar behaviour of talus in babies compared to cartilages where, a confined analysis was also carried out.
Figure 2.6 Mechanical behaviour of the cartilage fibrils as a function of tensile loads
(Nordin & Frankel, 2001)

Figure 2.6 shows the orientation of cartilage fibrils under different loading conditions for a tensile test where, the direction of the fibrils tends to be aligned as the load increases. This way, fibrils in the toe region are unaligned in comparison to the linear region until fracture (Nordin & Frankel, 2001).

Cartilages are important tissues to be considered during clubfoot correction, mainly for the correction of clubfoot in babies and children. This is because the amount of this tissue is higher in babies and children compared to adults and its mechanical properties change with the passage of time as people get older. Also, cartilages mark the difference between childhood and adulthood. In children, there are big spaces between bones and those areas are filled with cartilage. That is important when analysing adults’ or children’s feet because, the mechanical properties of soft tissues change in both cases.
2.3.4 Muscles, ligaments and tendons

Muscles are soft tissues in the human body that enable locomotion. They have the flexibility to expand and contract due to their viscoelastic behaviour. There are three types of muscles: smooth, cardiac and skeletal from which, skeletal are the main of these categories found in the foot. Skeletal muscles are the category of muscles in the foot.

Skeletal muscles: They enable the movement of the different limbs of the human body. They are found along the skeleton and react to voluntary movements. They have, as well as the other two kinds of muscles, the characteristic of being contracted. The disposition of fibres is parallel along the muscle and striated.

The foot contains a diversity of muscles which are referred as intrinsic, situated in the foot, to enable the movement of the toes, and extrinsic, located in the lower leg and connecting the foot to the leg. One of the most relevant extrinsic muscles is the calf, also named as gastrocnemius. Figure 2.7 shows the main extrinsic muscles classified in four groups: superficial posterior, deep anterior, anterior and lateral.

![Extrinsic muscles of the foot](image)

Superficial posterior muscles enable plantarflexion of the foot, while deep posterior muscles enable plantar flexion and inversion. Anterior muscles enable dorsiflexion,
inversion and foot toe extension where extensor hallucis longus terminates at the end of the big toe and starts in the mid-fibula. The lateral muscles enable eversion of the foot.

On the other hand, *intrinsic muscles* have the function of providing stability to the foot, mainly with the muscles in the plantar fascia to provide stability to the arches of the foot. Foot pathologies, for example, flatfoot or cavus foot, involve the muscles and ligaments in the plantar fascia, providing different stress distributions in comparison to normal feet.

They can be classified into four layers according to how deep the muscles are. Figure 2.8 shows this classification where different muscles are involved in every layer.

![Figure 2.8 Intrinsic muscles of the foot](image)

Figures 2.9, 2.10 and also, 2.11, show a more graphical representation of some of the most important muscles of the foot. The Figures provide the location of the muscles and other important tissues of the foot such as tendons.
Chapter 2 Anatomy, pathologies and clubfoot treatments

Figure 2.9 Lateral views of foot and tendons
http://www.podiatrychannel.com/pod/Images/ft_sdvw.gif

Figure 2.10 Muscles and tendons in the frontal view of the foot
http://www.podiatrychannel.com/pod/Images/ft_frntvw.jpg
Ligaments are vast soft tissues in the foot and ankle and are vital to join bones to other bones. Their composition is based on collagen fibres, and they are similar to tendons, but the function of the latter, tendons, is to join muscles to bones. Another main difference of ligaments compared to other soft tissues such as muscles is that they restrict the movement, in particular directions (Tyldesley & Grieve, 2009).

Some of the most important ligaments and essential tendons to consider for clubfoot correction are those around the ankle because they tend to be wider and stiffer. The major ligaments surround the ankle connecting the tibia, fibula, talus and calcaneus. This is because: a) this area distributes most of the weight in a standing position and before starting walking, b) the ankle has a primary function to provide stability. Table 2.1 summarises some important ligaments whose mechanical properties have been investigated and reported in the literature.
### Table 2.1 Some of the most important ligaments around the ankle\(^1,2,3\)

<table>
<thead>
<tr>
<th>Ligament</th>
<th>Linking Bones</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiC (Tibiocalcaneal)</td>
<td>Tibia and calcaneus</td>
<td>Medial</td>
</tr>
<tr>
<td>PTT (Posterior Tibiotalar)</td>
<td>Tibia and talus</td>
<td>Lateral-Posterior</td>
</tr>
<tr>
<td>ATT (Anterior Tibiotalar)</td>
<td>Tibia and Talus</td>
<td>Medial-Anterior</td>
</tr>
<tr>
<td>ATiF (Anterior Tibiofibular)</td>
<td>Tibia and Fibula</td>
<td>Lateral-Anterior</td>
</tr>
<tr>
<td>ATaF (Anterior Talofibular)</td>
<td>Talus and Fibula</td>
<td>Lateral-Anterior</td>
</tr>
<tr>
<td>CF (Calcaneofibular)</td>
<td>Calcaneus and Fibula</td>
<td>Lateral</td>
</tr>
<tr>
<td>PTaF (Posterior Talofibular)</td>
<td>Talus and Fibula</td>
<td>Lateral-Posterior</td>
</tr>
<tr>
<td>PTiF (Posterior Tibiofibular)</td>
<td>Tibia and Fibula</td>
<td>Lateral-Posterior</td>
</tr>
<tr>
<td>LTaC (Lateral Talocalcaneal)</td>
<td>Talus and Calcaneus</td>
<td>Lateral</td>
</tr>
<tr>
<td>MTaC (Medial Talocalcaneal)</td>
<td>Talus and Calcaneus</td>
<td>Medial</td>
</tr>
<tr>
<td>LPF (Lateral Plantar Fascia)</td>
<td>Bones of plantar fascia</td>
<td>Lateral</td>
</tr>
<tr>
<td>CPF (Central Plantar Fascia)</td>
<td>Bones of plantar fascia</td>
<td>Central</td>
</tr>
<tr>
<td>MPF (Medial Plantar Fascia)</td>
<td>Bones of plantar fascia</td>
<td>Medial</td>
</tr>
<tr>
<td>PTaC (Posterior Talocalcaneal)</td>
<td>Talus and Calcaneus</td>
<td>Posterior</td>
</tr>
<tr>
<td>CNL (Calcaneonaviculcar)</td>
<td>Calcaneus and Navicular</td>
<td>Plantar</td>
</tr>
<tr>
<td>CCL (Calcaneocuboid)</td>
<td>Calcaneus and cuboid</td>
<td>Plantar</td>
</tr>
<tr>
<td>TaNL (Talonaviculcar)</td>
<td>Talus and Navicular</td>
<td>Medial</td>
</tr>
<tr>
<td>TiNL (Tibionaviculcar)</td>
<td>Tibia and Navicular</td>
<td>Medial</td>
</tr>
<tr>
<td>ITaC (Interoseus Talocalcaneal)</td>
<td>Talus and Calcaneus</td>
<td>Central</td>
</tr>
</tbody>
</table>

1. \(\text{(Funk et al., 2000)}\), 2. \(\text{(Iaquinto & Wayne, 2010)}\), 3. \(\text{(Wei et al., 2011)}\).

Figure 2.9, as well as 2.10 and 2.11, show some of the most important ligaments and tendons in the foot and ankle in different views. The high amount of different soft tissues is one of the factors that make the foot complex to be analysed. Chapter 3
extends the review on ligaments, focused on modelling techniques and their mechanical properties, as this section intends to provide a brief and basic description of the anatomy and tissues of the foot.

The main tendon in the foot is *achilles tendon*. This tendon joins the calf with the foot bones, talus and calcaneus. Although Ponseti’s procedure is considered to be non-surgical, it comprises the foot tissues requiring a percutaneous tenotomy which is the section of the tendon to release pressure. Many surgical procedures commonly include the release of different soft tissues including the achilles tendon. The achilles tendon is the biggest and strongest tendon in the body, highly important to preserve the stability in the body (Lewis & Shaw, 1997). This tissue connects three muscles (plantaris, gastrocnemius and soleus) to calcaneus as shown in Figure 2.12.

![Achilles tendon and the connecting tissues](Lichtwark & Wilson, 2005)
2.4 Biomechanics of the foot and ankle

The foot and ankle enable people to perform different activities such as running, jumping or walking. The foot and ankle are relevant for an optimal biomechanical performance of the full body in those activities. Any related pathology in the foot and ankle can result in subsequent pathologies due to imbalances during the gait. For those reasons, the analysis of gait under different conditions has become important in the literature of biomechanics. Also, biomechanics of the lower limb is important to understand the behaviour of the elements of the foot as well as the medical conditions such as diseases, malformations, deformations, postural habits and others that can affect it. With the aid of biomechanical studies, it is possible to understand the forces that are in interaction with the body during movement.

The mechanical properties of living materials are more complicated to analyse than conventional materials. This is because their mechanical properties change depending on several variables such as patient’s age, nutrition, daily activities and so on. This is one of the principal factors to determine the modelling techniques and analyses reported in the literature from which, the modelling techniques for the analyses in this thesis were established.

In order to design an adequate analysis model, it is necessary to know the biomechanical behaviour of the limb and the mechanical properties of the tissues involved. For that reason, in this Chapter, the biomechanics of the foot is explained in order to establish the movements that describe different pathologies. Mechanical properties of tissues are described in Chapter 3.

2.4.1 Human planes and normal foot mobility range

If the foot is placed in a coordinate system, X (Mediolateral), Y (Anteroposterior), Z (Longitudinal), the foot deformities can be determined by the foot’s direction in the three human planes. Figure 2.13 shows the human body placed in a coordinate system with the three human planes, Sagittal, frontal and transverse.
Figure 2.13 Human planes (Hamill & Knutzen, 1995)

The first plane is the sagittal plane, defined by the Y and Z axes and dividing the body into right and left. The rotational movements of the foot about the ankle (or tibiotalar joint) and parallel to this plane are called plantarflexion and dorsiflexion (Chotel et al., 2005).

**Plantarflexion** is the rotation of the foot about the X-axis passing through the ankle such that the foot phalanges point downwards and distal from the tibia and fibula as shown in Figure 2.14 (a). The equinus deformity takes place in this plane by plantarflexion (Muñoz, 2006).

**Dorsiflexion**, also called extension, is the contrary rotational movement of the foot about the X-axis passing through the ankle such that the foot phalanges point upwards and draw closer to the tibia and fibula as shown in Figure 2.14 (a).

The adequate lateral range of dorsiflexion is 10 to 20 degrees from the horizontal (X) axis in order to have an adequate gait. In plantarflexion, this angle is from 20 to 50 degrees (Hamill & Knutzen, 1995).
The second plane, the frontal plane is represented by the X and Z axes. The two movements of the foot in this plane are called inversion and eversion.

**Inversion** is the rotational movement of the foot about the Y-axis passing through the ankle in the frontal plane such that the foot bones, seen from the plantar fascia point inwards as Figures 2.14 (b) and 2.15 (c) show. This movement defines the varus component of clubfoot.

**Eversion** is the contrary rotational movement of the foot about the Y-axis passing through the ankle in the frontal plane such that the foot bones seen from the plantar fascia point outwards as shown in Figures 2.14(c) and 2.15(b). This movement describes the valgus foot (Chotel et al., 2005).

The angles of inversion that make walking possible are between 4 to 6 but 6 to 7 degrees for eversion in a normal foot (Hamill & Knutzen, 1995). Figure 2.15 shows the wearing of a left shoe after a prolonged running period. Figure 2.15 (a) represents the shoe of a normal subject, 2.15 (b) shows the worn left shoe of a subject with 10 degrees of valgus foot as a result of eversion and Figure 2.15 (c) shows the worn left shoe of a subject with 10 degrees of varus, resulting from inversion of the foot during walking and running.
Finally, the transverse plane is identified by the X and Y axes and divides the foot into superior and inferior, as shown in Figure 2.13. The rotational movements in this plane are adduction and abduction where adduction is a component of clubfoot (Muñoz, 2006).

Adduction is the rotational movement of the foot about the Z-axis (vertical axis) passing through the ankle and the plantar fascia of the foot is on the ground such that the foot points to the inner position as shown in Figure 2.16. If the reference is a right foot, identified by the big toe and calf as shown in Figure 2.16, the foot turns to the left in adductus foot.

Abduction is the contrary rotational movement to adduction. Following Figure 2.16 as a reference, when the foot is placed on the ground, it turns to its external position in abductus foot. That is, for right foot abduction, the foot is turned to the right.
In the case of specific pathologies of the foot, various deformities can appear combined. It is important to define them in terms of the foot movements in the planes to provide more clarity when describing a full pathology. The movements of the foot are mainly produced because of the contraction of different muscles. The majority of the movements in the foot take place in the midtarsal and subtalar joint. That is why the bones in those sections of the foot have a higher deviation from the normal foot in the case of pathologies.

The movements involving the ankle, metatarsus and subastragalus result in supination and pronation. This is because foot movements are not entirely independent but combined (Muñoz, 2006).

**Supination** results from the concurrent movement of plantar flexion, adduction and inversion while **pronation** is caused by dorsiflexion, abduction and eversion (Muñoz, 2006). Some orthopaedists prefer to define clubfoot in terms of supination as it describes adduction, inversion and plantar flexion.
2.4.2 General description of the human gait

In a normal and healthy body, a simple gait cycle mainly takes place in the sagittal plane, while some pathology can involve the other two planes to be described. In this description, a simple gait is defined as one which displaces the body forwards and in a straight line. Activities such as running, involve significant movement in different angles in the three different planes rather than normal walking. For this reason, some authors describe it in the single sagittal plane while others in the three planes (Vaughan, et al., 1992). The human gait is such an ID card which distinguish people from each other, because minor differences can be found in people’s gaits. This is because the concept of normal foot could be vague.

The result of the gait is the movement of the body forwards by means of the friction between the surface and the foot. Different variables can be analysed in various scenarios to determine the variations in the gait. Some of them are the contact surface, the movement patterns, and the velocity of displacement, the impact forces or the necessary energy in the gait cycles.

The importance of the study of the gait has several implications and advantages. For example, in sports, it can be useful to determine the best deployment in athletes or for companies to improve and develop novel technologies for shoes. Also, this is relevant, because it provides information about the characteristics of a normal human gait, in order to compare it with pathological cases after their correction. In a healthy person, the centre of mass draws a sinusoidal pattern in the sagittal plane. The curve changes depend on the gait phase as shown in Figure 2.17.
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Figure 2.17 Human gait cycle (Abernethy et al., 2005)

Figure 2.17 describes the gait cycle of the swing gait giving information of the change in the angle of three joints in the sagittal plane: a) the hip, b) the knee and c) the ankle. The labels in the image correspond to IC; Initial contact, OT; Opposite toe off, HR; heel rise, OI; opposite initial contact, TO; toe off, FA; feet and TV; tibia vertical adjacent (Abernethy et al., 2005; Hosseinnia et al., 2011). The gait cycle, starting from a standing position or loading response until the terminal swing describes the full cycle as shown in Figure 2.18.

Figure 2.18 Normal gait phases (Vaughan et al., 1992)
2.4.3 The human gait after clubfoot correction

Assessment is a crucial phase to achieve the best possible results during medical treatment. It provides information to determine the right available treatment for every case. In addition, further assessments can provide feedback to change directions in the treatment or to conclude it after achieving the expected outcomes. It is important to emphasize that the end outcome after clubfoot correction is to recover the functionality of the limb enabling the patient to walk. Then, the primary outcome after clubfoot correction is to reach as much as possible a normal and painless gait in patients.

To determine the right correction, it is necessary to use as reference a healthy foot. Therefore, the normal gait is a parameter to assess the foot pathologies such as clubfoot. Although, human gait depends on several variables, the aim of this thesis is not to describe all of them, but to emphasise the importance of the gait after clubfoot correction.

Some studies in the literature analyse the differences in the gait of people with clubfoot and normal subjects. For example, a study conducted by Karol et al. (2005) analysed the gait after clubfoot correction. In their study, the patients ranked between 2 to 3 years old were evaluated by the Dimeglio scale to determine the severity. Twenty represents an extremely severe case on this scale while zero is a normal foot. The study organised the participants in four groups where: a) group 1, consisted of 36 patients whose clubfoot were treated by non-operative methods, b) the group 2, consisted of 5 patients, where percutaneous tenotomy was practised to treat the equinus component of the deformity, c) group 3, consisted of 14 patients, where tendo Achilles tenotomy and other posterior surgical procedures were applied to complete the treatment and d) group 4, 35 patients, where surgical posteromedial release was used as part of the treatment. The procedure involved the use of 12 Vicon cameras to collect kinematic data of the patient's gait. The Dimeglio score to assess the severity was 12.7 to 13.7 among groups, so the differences in severity among patients were not significant (P=0.74). The researchers found significant differences in the gait on the sagittal plane where 53.8% of the non-surgical cases achieved a normal sagittal gait for ankle motion after correction, concluding that non-surgical treatments had better results in this analysis. However,
Öberg et al. (1993) mention that some studies on gait analysis have limitations such as the reduced number of participants per group or few members distributed among various groups with different ages. In this study, group size is not the same among groups, and while it is similar between groups 1 and 4, the groups 2 and 3 are considerably smaller, principally the group 2 was 7.2 times smaller than group 1. This could be a variable to consider in determining the consistency of the results. Also, it is crucial to take into consideration that the gait patterns in two to three years old children can be different from better-established patterns in adults.

Other researchers Wren et al. (2005) evaluated the gait in terms of the visual evaluations such as the modified “Physicians Rate Scale” (PRS) which was used as a method to assess the gait for crouch, hip flexion, knee flexion and dorsiflexion in 13 subjects. Different observers reported their records. Their findings suggest that errors in this method can lead surgeons to infer contractures that do not exist. Then an incorrect assessment can result in relapse cases. In another study, Wicart et al. (2006) analysed the initial phase of the gait of 10 clubfoot patients and 10 normal patients aged between 10 to 11 years old. The researchers recovered data of the initial walking phases via Vicon systems to assess slow, medium and fast gait by obtaining the velocity of the centre of gravity. The results suggest less efficiency in the propulsion of clubfoot patients and showed differences between normal and clubfoot subjects walking efficiency after correction. The differences can be attributed to lower muscular capacities in the people affected by clubfoot. However, as well known, depending on different variables, the correction can be poor or efficient, opening up the possibilities for analysing the gait in different corrected clubfoot patients under various conditions such as age when treated and treatment techniques.

On the other hand, Öberg et al. (1993) conducted a study of the normal gait in patients from 10 to 79 in order to define the main parameters that describe it. The study consisted of registering the data from two photocells which were focused on walking patients, ten times with goniometers and three times without them. They analysed the average values for three gait parameters, V (velocity when walking), F (Step Frequency), L (Step Length) where $T_N$ is the time for $N$ steps, $T_D$ is the time of the walking cycle, D the distance between lights in Figure 2.19, as starting and ending points (between 0 and 1, the starting point and, between 10 to 11, the end of the walking
cycle, according to Figure 2.19). N equals the number of steps as shown in Figure 2.19. This is determined as follows:

\[ V = \frac{D}{T_D} \text{ cm/s} \quad (1.1) \]

\[ F = \frac{N}{T_N} \text{ Steps/s} \quad (1.2) \]

\[ L = \frac{V}{F} \text{ cm} \quad (1.3) \]

\[ \text{Figure 2.19 Visual description of the walking parameters in the normal gait for adults aged 10 to 79 years old (Öberg et al., 1993)} \]

Statistical data analysis by Öberg et al. (1993) suggests meaningful differences between men and women where women present higher step frequency than men but relative slower gait velocity, 118-134 cm/s for men compared to 110-119 in women. As well, the study reports differences in the velocity of older subjects: 0.1 to 1.3 m/s. Another significant difference was the changes in the walking patterns outdoors and indoors. This study showed that the label ”normal foot” can be relative because normal subjects present differences in their mobility range depending on variables such as age or gender.

These few studies emphasize the importance of the outcome when analysing current treatments and developing novel ones. It is important to consider that a proper and painless gait is the objective to achieve after clubfoot correction. One way to determine a right correction is comparing the gait in normal subjects against clubfoot patients after correction.
2.5 Introduction to the foot and ankle pathologies

The foot and ankle have the primary function of providing mobility to the human body. This is possible through electrical impulses from the brain to the terminals in the tissues surrounding bones. Any alteration in the limb, making it difficult to accomplish its principal function, results in foot pathologies. In addition, pain is a considered variable when determining an associated pathology.

The clinical assessment, usually offers information about different birth conditions. Main pathologies can be detected since childhood and further procedures to assess it such as MRI Scans, CT Scans or X-rays can be used to determine the severity and the right available treatment. The first step is to detect a possible deformity. Paediatricians commonly detect it in a general assessment after birth. Upcoming assessments can be performed to diagnose the right pathology. The proper assessment tools provide information to determine the correct diagnosis and treatments which vary from simple to severe or relapsed cases. In relapse cases, it is required to reassess the patient to determine a different procedure as Figure 2.20 shows.

![Diagram](image.png)

*Figure 2.20 Course of action for foot deformities correction*
Pathologies in the foot are a frequent combination of two or more different deformities. Thus, it is common in the clinical inspection to detect many of them to be treated. Clubfoot or talipes equinovarus is an appropriate example, where four different medical conditions, cavus, varus, equinus and adductus are combined to describe the pathology. Table 2.2 summarises the different possibilities according to the movement of the foot and articulations.

Table 2.2 Normal movements of the foot and its relationship to different deformities
(Muñoz, 2006)

<table>
<thead>
<tr>
<th>Articulation</th>
<th>Movement</th>
<th>Deformity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankle</td>
<td>Dorsiflexion</td>
<td>talus</td>
</tr>
<tr>
<td></td>
<td>Plantar flexion</td>
<td>equinus</td>
</tr>
<tr>
<td>sub astragalus</td>
<td>inversion</td>
<td>varus</td>
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2.5.1 Pes-adductus

It is a deformity of the forefoot involving the phalanges, the big toe and the metatarsus. In this deformity, the foot phalanges point inwards starting from the metatarsus and ending with the big toe separated inwards from the rest. It can be flexible or rigid, and it occurs in 1 of every 100 babies, being attributed to the intrauterine position of the foetus (Sankar et al., 2009). The contrary case is called pes abductus. Pes adductus is commonly referred as a component of the clubfoot deformity (Otremski et al., 1987). Although it is a clubfoot component, it can be developed in some patients without the presence of the other clubfoot components. Also, it can be unilateral as shown in Figure 2.21.
The aetiology is unclear, and the majority of the cases (87%) are usually corrected before the age of 6 and another additional 8% at the age of 16 giving good expectancy of correction for this deformity (Jackson & Stricker, 2003; Chotel et al., 2005). However, it requires being detected at early stages in the childhood to achieve a better correction, principally in rigid adductus feet. This pathology usually gets corrected spontaneously in most of the cases (95%) when the assessment results to be flexible metatarsus adductus (Widhe et al., 1988; Sankar et al., 2009). This suggests that adductus deformities that do not involve another component do not require treatment. However, this mainly applies to the flexible cases. For the severe rigid cases, the treatment consists of manipulations resulting in less than 2% relapse cases, considering that if the assessment was made in older children, the response to conservative treatments is poor requiring surgery (Muñoz, 2006).
2.5.2 Cavus foot

Cavus foot, which is also known as pes-cavus, is a deformity of the foot distinguished by a big hollow in the arch of the foot. Normally, the foot has contact with the ground. The clinical observation, in this case, shows the contrary of flatfoot. It is not a pathology that can be found in the first years of development; it is more frequent after the age of five. The mid-foot bones are higher than the usual position. The most common causes of pes-cavus are neurological, hereditary or neuromuscular. It has been associated with Charcot-Marie syndrome. Figure 2.22 shows the frontal and lateral view of cavus foot in adults where the arch is higher than normal feet.

![Figure 2.22 Pes cavus in medial view and both feet and (Muñoz, 2006)](image)

Other possible causes are associated with the weakness of different soft tissues, arthritis, contractures in the plantar fascia, congenital problems, imbalances of the muscles, and so on (Brewerton et al., 1963). Pain cannot be a particular symptom even if metatarsal bones are under compression, but sometimes, depending on the level of care, it results in a painless experience. Flexible pes-cavus foot is easier to treat with orthotic devices while a rigid one has additional problems such as calluses in the metatarsals resulting in a smaller contact area. For this reason, rigid cavus feet are prone to develop fractures (Franco, 1987).

2.5.3 Flatfoot

Flatfoot is a general expression to make reference to the condition where there is not visible arch of the foot which means that in a standing position, the mid-foot bones (the
arch) are displaced closer to the ground compared to a normal foot. Commonly, newborn babies, present flatfoot until they are four years old, and then, the bones, muscles, ligaments and tendons grow, taking their usual normal position. This common foot deformity can be flexible or rigid, combined with other deformities or the single flatfoot. In the case of a single flatfoot, it tends to be more rigid resulting in a reduced range of motion in the midfoot and hindfoot (Harris et al., 2004). Figure 2.23 clearly shows in (a) a flatfoot where there is no arch.

Figure 2.23 Flatfoot a) lateral view and b) rear view (Yeagerman et al., 2011)

Different names have been attributed to this very common pathology. Sometimes it is appointed in the literature as pes-planus or fallen arch (Franco, 1987; Pisani, 2010). The lack of consensus on the terminology can result in confusions (Yeagerman et al., 2011). Although flatfoot can be painless in some cases, the improper correction results in varus knee due to the forces produced by the foot pronation, then producing knee pain and upper limbs affections such as scoliosis in vertebrae (Franco, 1987).

There are different ways to assess flatfoot. Firstly, the observational assessment of the gait in patients, consisting of identifying problems to execute toe and heel walking, is a primary assessment procedure. Pronation in a flatfoot stance gait is about 10 to 12 degrees compared to 4 to 8 in a normal foot (Franco, 1987). Flatfoot can be assessed
using X-rays, MRIs, CT scans and other gait analyses. Also, there are different procedures to correct it depending on the assessment results (flexible or rigid flatfoot). Those procedures can vary; they include the use of prostheses and insoles.

2.5.4 Varus foot

This pathology is described by the inversion of the heel and phalanges, starting from the metatarsus in adduction and inversion (Muñoz, 2006). As varus is not an isolated deformity, it can be found combined with other deformities, for example, in clubfoot with adduction, cavus and equinus. The most severe combination and most common deformity is talipes equinovarus, where the varus foot is combined with other deformities.

Figure 2.24 Contrast of two pathologies in the foot, Varus and Valgus in the left foot

Figure 2.24 compares two very common deformities of the foot, valgus and varus. In contrast to normal feet, the heel is inwards in varus feet while outwards in valgus. In the case of clubfoot, cavus is a consequence of the adduction and inversion of the foot. The varus adductus results in abnormal gait and depending on the severity and the combination of associated deformities, different treatments can be suggested such as the use of insoles, manipulations or fixators.
2.5.5 Valgus foot

Valgus foot is described as the one with the heel in eversion and the phalanges in abduction and eversion (Muñoz, 2006). Contrary to varus deformity, the heel points outwards and twisted with respect to the ankle from the rear view. Calcaneo-valgus commonly referred to as the predecessor of flatfoot, is the opposite of equinovarus (Evans, 1975). As a consequence of this deformity, valgus knee can result from valgus foot. This can affect the normal gait of patients and in some of them, it causes pain.

The bones in valgus feet are structurally normal, and a common treatment consists of using manipulations to correct the deformity when the foot is flexible (Muñoz, 2006). However, other techniques can be used to treat severe cases. Figure 2.25 shows an example of a patient with two deformities, cavus-valgus, where the heel is outwards describing the valgus component and a visible higher arch compared to normal feet.

![Figure 2.25 Pes cavus-valgus (Muñoz, 2006)](image)

2.5.6 Equinus foot

Equinus foot or pes equinus is a deformity characterised by plantarflexion with respect to the leg where the patient is constrained to perform toe walk. However, this deformity is commonly accompanied by other deformities such as equinus varus or equinus valgus (Muñoz, 2006). Also, this is a component of clubfoot. The deformity results in a shorter Achilles tendon requiring, in some cases, Achilles tenotomy to release pressure in the tissue. Other treatments such as the Ilizarov technique can be used to correct complex deformities that involve equinus. This deformity is possibly caused in some cases by
cerebral palsy and knee hyperextension that causes changes in the normal gait (Higginson et al., 2006). As shown in Figure 2.26, the maximum angle between tibia and talus is 115 degrees in plantar flexion in normal feet. Higher values are associated with equinus foot (Kirienko et al., 2003).

![Figure 2.26 Angles of the foot for plantarflexion (Kirienko et al., 2003)](image)

**2.5.7 Talipes equinovarus (clubfoot)**

Clubfoot, as well named Congenital Talipes equinovarus, is one of the most common foot deformities in paediatrics (Sanzarello et al., 2010; Regondi et al., 2012), involving the foot’s musculoskeletal system in the pathology (Sanzarello et al., 2010) the angle between calcaneus and astragalus is necessary to determine the deformity and its severity. The relationship between these two bones determines conditions as flatfoot when the angle is bigger than 40 degrees or talipes-equinovarus when it is smaller than 40 degrees. In the next sections, the pathology is explained thoroughly, starting with the general description of the pathology, and therefore the aetiology (origins of the pathology), diagnosis and ending with the treatments and prognosis.
Figure 2.27 shows a baby’s feet affected by bilateral clubfoot. In a clinical study directed by Canto et al. (2008) they reported bilateral clubfoot in 70.7% of their treated patients while Bakalis et al. (2002) referred (52%). In both cases, bilateral clubfoot is more frequent than unilateral either right or left foot. Also, Figure 2.27, (a) clearly shows the inversion of the foot resulting in varus. In 2.27 (b), it is possible to distinguish the adduction of the foot where the big toe is pointing inwards, the plantar flexion where the heel is close to the tibia in the posterior foot, resulting in equinus and a shorter Achilles tendon and the cavus component in the midfoot. Cavus in clubfoot is produced by the other three components. Figure 2.28 shows the shape of the bones in a baby affected by clubfoot where the four components of this pathology are able to be identified.

Figure 2.27 Severe clubfoot in babies a) frontal view b) rear view (Krauspe, 2011)

Figure 2.28 Different views of the bone’s shape of a clubfoot baby
2.6 Clubfoot pathology

In the clinical inspection, clubfoot is identified by its similitude with a golf club and functional criteria of the clinical inspection such as gait difficulties, pain and the angles between bones. In clubfoot, the forefoot and the midfoot are inverted, and the big toe seems to be shorter than in normal feet. The forefoot is equinus, and the talus is displaced upwards and inverted. The calf in these cases looks stunt. The anatomical description suggests that the calcaneus is rotated such that it points inwards. This results in the varus component. In comparison, a normal foot is pointing to the exterior and the astragalus is positioned in proximity to the malleolus of the tibia.

Radiographs in dorsi/plantar flexion and lateral positions display the angle of the astragalus and calcaneus which is about 20 to 50 degrees. Although, radiographs are not the only assessment procedure to support the clinical observation; they are useful to determine the severity and complement the assessment.

The aetiology of clubfoot is still diverse and unknown but some of the main possible causes are intrauterine deformations due to certain foetal positions, consumption of drugs, alcohol and cigarettes during pregnancy, history of people with talipes equinovarus in members of close family, genetics and so on.

Treatments to consider are different depending on the severity, previous diagnosis, final outcomes, and so on. Some of the most successful methods reported in the literature are Ponseti method, Kite the French method as conservative procedures and the Ilizarov method for relapse and severe cases. Also, the Ilizarov frame is useful to correct fractures and other pathologies.

Clinical inspection offers more information in addition to radiological inspections and the success of the treatment depends directly on the right diagnosis and prompt treatment before the baby becomes six months old. Treatments and assessment procedures for clubfoot are different for babies, children and adults. This is because foot tissues tend to be stiffer as people get older. While babies are commonly treated with conventional procedures, adults require surgical and non-conventional methods because of the stiffness of their tissues.
2.7 Clubfoot aetiology

Clubfoot aetiology is still diverse and uncertain. As a result, many variables have been associated with the possible causes of this congenital condition. The literature on the aetiology is diverse, and research on this subject continues as this knowledge could be used to prevent this pathology. Nevertheless, some of the main causes of this pathology are mainly focused on genetics, anatomy, embryology and the role of soft tissues. A proper understanding of the causes of clubfoot leads to establishing better treatments, as well as prevention methods. For this reason, the research on the aetiology still continues.

The United Kingdom has an incidence of clubfoot cases of about 1 in 1000 of newborn babies, compared with the Polynesian population, which has about six times more cases (Cooke et al., 2008). Another important aspect to consider is that three of every four kids diagnosed with clubfoot are male and more than 50% of newborn babies have this deformity in both feet (Cooke et al., 2008). This statistics justifies the importance of the studies about clubfoot treatments, and its aetiology, due to the high number of cases in different ethnic groups.

Genetics is undoubtedly an important factor to consider, and that is why this cause has been studied during the past years as part of the aetiology. Jackson and Stricker (2003) argue that if one of the parents has been diagnosed with clubfoot, the risk of procreating a child with this condition increases by 25%.

Other causes of clubfoot can be correlated with alterations in the foetal development. In the later developmental stages, the foot acquires equinus and varus positions. This is because the foetus grows, and space in the placenta becomes smaller. During the foetal development, two phases of bones growth can be distinguished: the tibial and fibular. When toxic chemicals such as glucocorticoids are ingested by the foetus during the fibular phase, the child can be born with clubfoot (Victoria-Diaz & Victoria-Diaz, 1984). This argument supports the idea that environmental changes can increase the risk of congenital deformities.
Other factors such as substances consumption by parents were studied by Honein (2002) who investigated the smoking habits of parents and their genetics including, history of relatives with clubfoot. The results suggest that smoking during the first three months of the intrauterine development can be a possible cause of clubfoot as well as having a close relative with this deformity.

Even if the aetiology is complex, there is comorbidity with diseases such as Charcot-Marie syndrome, meningomyelocele or encephalitis (Malizos et al., 2008). In other investigations, Wynne-Davies et al. (1982) found a relation between talipes equinovarus with haemorrhage and hypertension in mothers of clubfoot patients. In addition, Malizos et al. (2008) suggest that Talipes Equinovarus has been associated with antepartum haemorrhage as one of the factors and maternal hypertension. Nevertheless, in this study, no association with intrauterine pressure was found.

Alterations in muscles, ligaments and tendons have an important role in the aetiology of clubfoot. Fibres of muscles subjected to high tension could be responsible for causing clubfoot (Ballantyne & Macnicol, 2002). Moreover, Cooke et al. (2008) considered the importance of soft tissues in the aetiology and argued that there is no doubt about the relation between soft tissues and clubfoot. However, there is not a full understanding of the involved forces that promote clubfoot. Other researchers Feldbrin et al. (1995) analysed the relation between clubfoot and the muscle imbalance and found a correlation with the level of severity in patients.

On the other hand, Browne (1959) identified two types of deforming forces. The first one is the malposition of the foetus, which results in the increasing of the mechanical intrauterine pressure because feet push against the uterine surface. However in obstetrics and embryologic literature there is not a conclusion that suggests it to be the cause of clubfoot. The second one is the hydraulic pressure by the amniotic liquid which increases the inner uterine pressure and can cause atrophy of muscles.

More possible causes are still being analysed to try to find the causes of clubfoot. The importance of the study of the aetiology is transcendent because it affects directly the use and development of novel methods to correct the deformity and also, because it influences the advancement required in the research and technology to prevent it. At
present, a vast research in this field is still being carried out in order to get a higher rate of success in the treatment of clubfoot.

2.8 Clubfoot assessment and diagnosis

Clubfoot assessment is usually carried out by the paediatrician during the first days after the birth. Depending on his general assessment, the patient can be remitted to other specialists such as surgeons or orthopaedists.

The assessment is the most important stage to guarantee reliable results for the clubfoot correction because it provides information to determine: a) the right pathology, b) the level of severity and c) the most adequate treatment. Usually, relapse and neglected cases result from mistakes in the assessment. When clubfoot is not properly assessed before the six months old, the soft tissues get stiffer. Therefore, corrective procedures tend to be operative as the patient get older. Those mistakes can be attributed to: a) The lack of training to perform corrective procedures, b) an improper assessment, c) misinformation on the corrective procedures by parents, d) the lack of infrastructure, e) an inefficient health service and so on.

Normally, the assessment is based on different methods such as X-Rays, ultrasounds, MRI’s, CT scans and others. The first part of the assessment is the clinical observation because it gives enough information to suspect about foot pathologies by detecting pain or unconventional foot angles. Secondly, the use of X-Rays and pain scales results in a more accurate assessment. Another way to assess clubfoot is using ultrasound which makes it possible to observe changes in talus and navicular joints before birth. Ultrasound can predict clubfoot in 83 % of the cases (Macnicol & Murray, 2008). Tillett et al. (2000) argue that in 61% of cases after diagnose, surgery is necessary to correct the deformity.

Different authors (Jackson & Stricker, 2003; Bar-On et al., 2005; Siapkara & Dunkan, 2007; Cooke et al., 2008; Macnicol & Murray, 2008) suggest radiographs as a reliable method of assessment and ultrasounds in order to make a diagnosis before the birth.
X-rays have been suggested by clinicians for the assessment. Even if the use of X-rays is not by routine, they can be immediately ordered when there is suspicion of clubfoot (Anand & Sala, 2008). On the other hand, different scales determine the severity of the condition. One of the most popular to assess clubfoot is the one developed by Pirani. According to statistics, 83% of cases result in a positive diagnosis and the remaining cases are not well assessed. In this case, the Pirani score, which defines the level of contracture of the hindfoot and midfoot, has been suggested as good alternative to determine the level of severity (Siapkara & Duncan, 2007).

Some of the mentioned procedures in a further section of this Chapter have been reported with a high level of success. Depending on the method and the assessment, good outcomes can be achieved. However, relapsed clubfoot cases usually require a reassessment. Then, some severe and relapse cases may require unconventional procedures. For this reason, it is crucial to determine how severe the deformity is and emphasise the importance of the assessment stage.

### 2.9 Clubfoot treatments

Since Hippocrates described his understanding of clubfoot, many treatments have been developed and modified over the time. This is because some treatments have been reported to fail in some patients while in others; they have not provided the expected outcomes. Undoubtedly, the development of technology, manufacturing methods, and the upgrade of novel techniques are important variables to consider when talking about the progress in treatments and outcomes.

Conservative methods, which are taking advantage of at present, such as orthosis or casting, report a high rate of success that goes from 20 to 80% (Jackson & Stricker, 2003). Also, the medical community supports the idea of considering the non-operative methods as the first option to treat clubfoot (Sud et al., 2008). Moreover, surgical procedures are sometimes necessary in relapsed and complicated cases. The rate of success varies in the literature, reporting differences among some methods such as Ponseti, Ilizarov, Dimeglio or the French method. Tenotomy still continues to be
practised but depending on the assessment, and the severity of the case, methods to correct clubfoot can vary in every patient. Patients, treated after birth, have shown optimal results with conservative treatments such as Kite’s method but there are possible relapsed cases in patients treated when they are six months old or older (Fripp & Singer, 1953). In those cases, some surgical techniques such as the Ilizarov procedure can be a reliable alternative.

On the other hand, history has a significant role to play in order to understand the advances and failures of different techniques. This helps to determine the philosophical path to analyse, develop and modify procedures. Also, history contributes to understand the changes in the philosophy of treatment over the time. For example, treatment tendency has changed from mostly surgical procedures to mainly non-surgical methods at the moment (Singh et al., 2013). Also, it provides information to identify critical issues to correct previous errors in procedures. In the case of clubfoot, a historical overview helps to explain possible failures in the treatments over the time. It enables: a) to establish the background on clubfoot treatments to define the appropriate experimental and numerical analyses and b) to modify the current methods and techniques in order to improve procedures.

Indeed, various methods have been used in the constant effort to correct clubfoot to enhance the life quality of people affected by this deformity. For those reasons, in the next sections there is a brief review of some transcendent methods and techniques involved in the clubfoot correction. Firstly, a historical overview of the procedures is presented; this is followed by distinguishing between surgical and non-surgical methods, their advantages and disadvantages. Finally, in further sections of this Chapter, there is a comparison between the Ilizarov method and its differences with other useful methods at the present time.

Figure 2.29 summarises some of the most remarkable treatments for clubfoot divided into operative or surgical procedures and non-operative (non-surgical or conventional treatments). The current literature review focuses on those treatments with high relevance to the clubfoot history because the aim is not describing all the existing procedures but to summarise some of the most remarkable to compare with the Ilizarov treatment.
2.9.1 Historical overview of clubfoot treatments

The first archives about clubfoot treatments were drawings and paintings made by the Egyptians and Indians in about 1000 B. C (Miedzybrodzka, 2003). Then, around 400 B. C, Hippocrates distinguished some important aspects of the treatment of clubfoot such as the importance of the prompt correction as soon as possible after birth (McCauley Jr, 1966; Dobbs et al., 2000; Miedzybrodzka, 2003). He noticed that clubfoot could be corrected by means of bandages and manipulations of the foot and ankle, providing fair enough results. This development became transcendent because some of the actual
methods operate under the same corrective procedures using bandages (Dobbs et al., 2000).

Hippocrates’ approach on clubfoot treatments seemed to be forgotten for years until the beginning of the 19th century when Scarpa published an article on this subject (Dobbs et al., 2000). Then, Scarpa developed a method that involved a non-surgical treatment employing an external frame to correct the deformity. Almost at the same time, Timothy Sheldrake proposed another corrective procedure based on the Hippocrates approach on the importance of the early correction. Additionally, he considered the role of the ligaments and muscles to achieve a proper correction (Dobbs et al., 2000).

Between 1830 and 1930 the operative methods became more relevant than conventional procedures. Achilles tendon tenotomy and other different procedures related to the soft tissues correction had high impact at that time. This fact was due to continuous progress in the field of anaesthetics, promoting the development of new surgical techniques in medicine.

The Achilles tenotomy had a substantial impact on the history of clubfoot correction. For this reason, researchers changed their previous opinions to consider this procedure as an option. For example, Ponseti method includes a simplified variant of this procedure in one stage of the treatment. The first person who tried to implement the tenotomy for the clubfoot correction was Delpech in 1823 (Dobbs et al., 2000). However, as a result, of the operation in patients he treated, he observed the presence of sepsis (i.e. Infections). This observation slowed down the initiative of the medical community to implement the procedure. Then, another surgeon, Stromeyer, continued applying the Achilles tenotomy but achieving outstanding results in comparison to Delpech’s procedure due to the absence of any sign of infection after the operation. After some years, he applied this treatment on W.J. Little, an English surgeon, correcting the deformity he had after suffering poliomyelitis (Stromeyer, 1834; Little, 1839). Then, after Stromeyer trained Little, they kept practicing the procedure and improving the operation (Stromeyer, 1834; Fripp & Singer, 1953; McCauley Jr, 1966). However, this operative method by sectioning the tendon just provides partial correction, just the equinus component in clubfoot (McCauley Jr, 1966).
In subsequent years, another surgeon, Adams, pointed out the error of sectioning the Achilles tendon (Dobbs et al., 2000). Then, Rogers and Dickson developed in 1834 but, applying it widely till 1866, the subcutaneous tenotomy, which is a simpler and easier procedure, with minor complications compared to the Achilles tenotomy (Dobbs et al., 2000). They studied the effects of this procedure with several new-born babies; they noticed that the only bone that presented a considerable serious deformity in clubfoot is the talus. Adams considered Scarpa´s method as inefficient as well as other existing mechanical methods to treat clubfoot. This is a relevant aspect to be distinguished in the history of clubfoot treatments because it allows identifying the current philosophy in the treatment of clubfoot at those times. The anaesthetics procedures were improved and surgeries displaced the conventional methods. After some time, in 1891 Phelps included soft tissues and the division of ligaments in the surgical procedures, in addition to the Achilles tenotomy (Dobbs et al., 2000). Another important aspect was the introduction of radiographs to determine the level of severity of clubfoot. Subsequently, by implementing novel assessment methods, different procedures were developed due to the improvements of antiseptics which highly promoted surgeries. Then, Elmslie (1920) emphasized the importance of immobilising employing of plaster-of-Paris. This is a relevant aspect because further methods such as the French method and Ponseti method apply similar principles using a percutaneous tenotomy and, on the other hand plasters as part of his procedure.

Various methods were developed including talectomy for the correction of the bones in the foot. Despite these advances in the operative treatments of clubfoot, after 1900, the non-surgical methods recovered prevalence even if surgical ones continued to be developed.

In 1930, Kite suggested that manipulative methods provide good results without complications for the treatment of clubfoot, promoting casting as a reliable alternative. Few years later, Browne (1937) developed a corrective procedure by using a bar between the feet to correct the deformity. In further years, methods developed by Ponseti, Bensahel and Dimeglio attracted the attention of the specialists due to the statistics of success and low rates of side effects. Ponseti’s procedure involves the use of a corrective bar similar to the one developed by Browne. Those procedures are explained in the next section about the surgical and non-surgical methods.
In the current time, the criteria to choose among operative and non-operative procedures depend on the assessment carried out by the surgeon in charge. One of the most relevant considerations to decide among treatments is: a) the level of the severity, b) patients’ age, c) relapse and failure history of previous treatments. Ponseti’s method has been reported in the literature as a successful procedure because of statistics, pointing out the good results of his procedure. However, for relapsed clubfoot cases, severe cases of patients treated in adulthood, there are surgical methods that can be considered to treat clubfoot.

Next two sections contain the review of some of the current and most important methods based on their importance to the medical community. This makes it easier to identify their differences among treatments, their range of applicability and their differences with the Ilizarov technique.

2.9.2. Non-surgical treatments

Scarpa’s method

The Scarpa method for clubfoot correction was one of the first approaches to treating this deformity, remarking that Scarpa was one of the most important people in the history of clubfoot treatments. As an anatomist, he made many contributions to medicine and anatomy. One of them was the development of the first clubfoot orthosis registered in the literature in 1803. Scarpa described in his publications the analyses he made about the anatomy of clubfoot based on his results of sectioning numerous cadavers with this medical condition. Then, he explained the relationship that bones hold with the causes of clubfoot according to his understanding of this pathology (Parigi, 2004). Scarpa’s orthosis consisted of a hard base, resembling a shoe and connected to a belt down to the knee by a rigid bar. Depending on the case, gradual adjustments induced the correction of the position of the foot. In the current time, the Scarpa’s frame is not frequently used to treat clubfoot, and it has been displaced by other alternatives, both surgical and non-surgical. Figure 2.30 shows the frame used for the Scarpa method.
Kite’s method

Another technique was developed by Kite (Kite 1939; Fripp & Singer 1953; Kite, 1972). The basis of this procedure is to consider the elements of the deformity, adduction, inversion and equines independently of each other. The order of correction has a significant role in achieving the best possible results where equinus must be the first deformity to be corrected to avoid relapse clubfoot. The process consists in the application of plasters, a precedent of subsequent similar techniques such as Ponseti’s and the French methods (Fripp & Singer, 1953).

Due to the similarities between the Ponseti’s regime and the Kite method, some studies have compared their efficiency where, Ponseti’s is reported to be more efficient as well as faster in the correction. Although Kite’s procedure has shown good results in the correction of about 90% when applied by Kite, other surgeons have reported poorer results. (Sud et al., 2008) The justification for the better results with Ponseti’s regime could be due to the vague and inadequate explanation of Kite’s procedures (Sud et al., 2008). Figure 2.31 shows the cast used in the Kite’s method.
The Ponseti Method

Maybe Ponseti’s regime is one of the most common conservative methods for clubfoot treatment due to the vast number of publications and conferences about this method, and probably it can be considered such as one of the most successful non-surgical treatments to date. Many authors have described his procedure (Ponseti, 1992; Dyer & Davis, 2006; Siapkara & Duncan, 2007; Anand & Sala, 2008; Cooke et al., 2008; Sud et al., 2008; Bronfen et al., 2009; El-Adwar & Kotb, 2010; Riffard et al., 2010). Also, some authors have compared other treatment procedures such as the French Method (Richards et al., 2008) and the Kite’s methods (Sud et al., 2008) with Ponseti’s.

The Ponseti’s procedure consists of the use of casting to correct the adduction of the clubfoot, initially as shown in Figure 2.32 (b). Then, subsequent modifications to the casting are done to provide correction. The percutaneous procedure of Achilles tenotomy is part of the treatment to release stress in that soft tissue, making the correction faster (Ponseti, 1992). An average of 3 to 5 casts is commonly required during the treatment. In addition, the final cast lasting for about three weeks is required (Richards et al., 2008). When adduction is corrected, the use of an external frame in the following months after the casting is part of the procedure. The external corrective device consists of a pair of shoes linked by a metallic bar with the possibility of adjusting the angle to maintain the position at 70 degrees of abduction and about 15
degrees in dorsiflexion. This measure is to prevent relapse clubfoot. Usually, this device has to be used during 3 to 5 years after the procedure. The time of use varies depending on: a) the severity, b) the outcomes and c) the right application of the casting since early age. It can be used at night or different intervals during the day. This frame, as shown in Figure 2.32 (a) reduces the probability of relapse clubfoot.

![Image of clubfoot treatment devices](image_url)

**Figure 2.32 The Ponsenti procedure a) external frame and b) Gradual casting (Staheli, 2009), [http://www.global-help.org/publications/books/help_cfponseti.pdf](http://www.global-help.org/publications/books/help_cfponseti.pdf)**

**Dimeglio & Bensahel’s method**

Between 1990 and 1996 two surgeons, Dimeglio and Bensahel, developed a non-surgical method that involves physical therapy as part of the treatment. Also, (Dimeglio et al., 1995; Dimeglio & Canavese, 2013) describe a method for the assessment of clubfoot based on the identification of the varus deviation, the equinus deformation, adduction and derotation. The scale proposed by Dimeglio on the classification of the severity goes from 0 to 20 points. From 1 to 5 it is the less severe with a high percentage of success after the treatment and from 15 to 20 it means a resistant and severe deformity. In this way, the evaluation can guide the doctor to determine the adequate procedures (surgical or non-surgical) based on the level of severity. Dimeglio and Bensahel method involves the use of passive motion machines to stimulate the peroneal muscles and the application of bandages. Even if this method has presented good results in some cases, it is not as popular as other ones due to the time it takes comparing it with other methods. A study that verifies the efficiency of this method reported that in 29% of cases, tendo Achilles procedure was necessary although, the procedure
produced good result in more than 70% of cases (Karol, 2005). Figure 2.33 shows the passive motion machines used by this treatment.

![Passive motion machines in a baby](image)

*Figure 2.33 Passive motion machines in a baby (Dimeglio et al., 1996)*

Dimeglio et al. (1996) argued that based on a study that they performed; this method can reduce the number of cases that require surgery. The passive motion machine is tolerated by children and can be used while they are sleeping without considerable side effects. The best results are obtained in the first three years after birth.

**The French method**

The French method is another commonly used conventional procedure, mainly in the USA and Europe. In contrast to Ponseti’s method, it requires daily manipulations (Dobbs & Gurnett, 2009) and the use of adhesive strappings to promote the deformity correction (Richards et al., 2008). Just like the Ponseti’s technique, it requires in several cases (about 85% of the patients) a percutaneous tenotomy (Singh et al., 2013). While Ponseti’s procedure results in a faster correction than the French method, the latter presents less relapse (29% by the French method vs 37% by Ponseti’s procedure) and a slightly higher rate of success (94.4% vs 95%) by the French method (Richards et al., 2008). Both methods are some of the most famous conservative treatments at present.
2.9.3 Surgical treatments

Achilles tenotomy

Several surgical methods have been practised clinically over the years for clubfoot treatment, particularly, after the development of anaesthetic procedures. Some of the most successful procedures have been strongly documented in the literature. However, many other procedures have not been broadly applied or have not been too popular. One of the first successful surgical procedures for clubfoot correction was the Achilles tendon tenotomy which consists of sectioning the tendon to release stresses and facilitate the correction, mainly the equinus component. Also, it has variations depending on the patient and the right pathology. This operation was first performed by Stromeyer (1834) and nowadays is part of some surgical procedures. The Ponseti’s method comprises a variant of this method in one of the stages, but the tenotomy is subcutaneous, making it easier, faster to perform, less invasive and more efficient.

Turco method

Another surgical procedure is the Turco method introduced by Vincent Turco in the 1970’s (Turco, 1971). This surgical procedure consists of making an incision of about eight to nine centimetres in the zone of the metatarsus. Therefore, this procedure is necessary to divide the Achilles tendon. After that procedure, it is possible to identify the talofibular ligament that will be also sectioned. Finally, the procedure continues by releasing the posterior, medial and subtalar tissues (Dobbs et al., 2000). This technique has three main difficulties: a) Postoperative stiffness of the foot, b) relapse due to early surgical procedures, and c) wound curing (Turco, 1971). Figure 2.34 shows the incision area in the metatarsus.
McKay and Simon’s method

McKay and Simon’s method is another treatment to correct foot deformities. This method consists of the release of the circumferential subtalar area in order to correct the talonavicular subluxation (articulation displacement by soft tissues position change). However, nowadays it is considered excessive (Dobbs et al., 2000). This procedure enables the correction of the equinus by means of the lateral displacement of the calcaneus.

Ilizarov Technique

Finally, one of the most successful operative methods is the Ilizarov procedure which uses an external fixator. Some advantages of this treatment in contrast to other surgical procedures are: a) the flexibility of the frame to be adapted to the requirements of every patient b) minor surgical complication compared to other techniques; c) it can be applied to complex deformities with reliable general results. Chapter 3 focuses on a broad description of this technique, including its applications, the medical considerations of the use of the frame, as well as the literature review on the numerical and experimental studies of the frame.

There are other surgical procedures for clubfoot correction such as those developed by Brockman in 1937 and Bost in 1960, (Anand & Sala, 2008). Another procedure is the rhomboid flap method by (Rejholec, 2001). Some of these procedures have been modified over the years. These methods are must recurrent in cases of relapsed or
severe clubfoot and usually are considered when other conventional treatments have failed. However, they are less popular than other surgical procedures.

2.10 Statistics and prognosis on clubfoot

Statistics for clubfoot correction vary depending on the country, and the corrective method determined by the surgeon in charge. Many other conditions can affect the number of cases in countries, principally depending on variables such as infrastructure, the economy of the country, the assessment procedures, the qualifications of the surgeons, etc.

Statistics on clubfoot incidence show that having one parent or both parents with clubfoot, or a history of clubfoot in the family can increase the percentage of having a clubfoot baby by 10 to 20%. Also, as the number of family members with clubfoot increases, the risk of having a kid with this condition rises (Siapkara & Duncan, 2007).

In a study performed by Swamy et al. (2009) reported that the prevalence of clubfoot cases is 2 per 1000 births. Shelton and Banton (2009) reported an incidence of 1 to 3 per 1000 newborn babies. Considering these statistics, the study of clubfoot, including assessment, treatment, aetiology and other related topics have a big importance in different scientific fields.

Results are correlated with the method of evaluation and the proper treatment. Pirani score can determine the necessity of an osteotomy in the treatment of clubfoot depending on the severity (Dyer & Davis, 2006). It shows the importance of the assessment to determine adequate treatments.

Conservative methods such as Kite’s method, Ponseti method or Dimeglio and bensahel’s method have been promoted by the international clubfoot study group in 2003 (Anand & Sala, 2008). Nevertheless, there are other techniques with a high success rate depending on the severity of the deformity such as the French technique, operative treatments or the Ilizarov technique.
Relapsed clubfoot is reported in 80% of cases in the first two years of life (Cooke et al., 2008). For that reason, sometimes, it is necessary to consider non-conservative methods or surgical ones in order to correct this condition.

According to the statistics presented in this section, clubfoot assessment can be difficult in some cases, and the prognosis is correlated with different variables such as attachment to the treatment, an early and appropriate treatment and the process of assessment.

2.11 Summary

Clubfoot is a complex foot deformity in the foot and ankle. In order to develop adequate models, comparable to the real case study, it is essential to know: a) the anatomy of the limb to be investigated (the foot), b) the differences between the Ilizarov treatment method, which is analysed in this study, and other treatment methods in order to understand their advantages, disadvantages and range of applicability, c) the most common pathologies of the foot in orthopaedics, in order to provide clarity in comparison to clubfoot, d) the assessment procedures, e) the biomechanics of the foot, and f) the historical background on the treatment of clubfoot. This Chapter has covered these aspects with the purpose of providing a basic understanding of the related literature for the development of the Ilizarov treatment method that is analysed in the thesis.

As a multidisciplinary project, it is essential to understand the anatomy and biomechanics of the foot, which is the limb involved in clubfoot. This will facilitate the correct choice of variables and the making of right assumptions and simplifications. Also, establishing the differences in the applications of the Ilizarov frame to different age groups will contribute to the identification of the differences between the Ilizarov treatment and other treatments. An important consideration to emphasise is the difference between non-surgical (conventional) and surgical treatment procedures as each procedure has its range of applicability.
CHAPTER 3

Review on the study of the Ilizarov frame and the foot tissues

3.1 Introduction

Modelling techniques are relevant to establish approaches to understand the behaviour and nature of things. Also, validation and verification of those models by analytical, experimental or other methods is important. However, it is difficult to create a model exactly the same as the real case study but reductions enable a simpler and faster approach that in most of the cases can provide enough accurate results. In addition, it is critical to identify the limitations of experiments and models. This is because of the nonlinear behaviour of most of the systems in nature. Then, approaches are required to linearize the problems to provide easier solutions. In the case of clubfoot, it involves non-conventional materials that are living tissues. For the analysis of living tissues, it is important: a) to choose the appropriate modelling techniques and b) to consider the right reductions to the model. This is because living tissues in contrast to conventional materials change their mechanical properties as functions of several variables. Then, the result of those considerations is obtaining a reliable model that represents the real case study as much as possible.

In this Chapter, there is a literature review of the current numerical and experimental studies on bones, soft tissues and the Ilizarov frame. This is important for many reasons. Firstly, it enables identifying the current modelling techniques and distinguishing their advantages and disadvantages. Thus, it leads to establish the most appropriate parameters for the analysis in this thesis such as mechanical properties, boundary conditions, loads, displacements, mesh techniques, mesh elements and so on. Also, it allows finding those conditions that have not been yet deeply studied on this research subject. On the other hand, the literature on the modelling of the Ilizarov fixator has been focused mostly on the independent analysis of the frame parts to identify their
mechanical properties. The few numerical and experimental studies on the frame assemblies have analysed the impact of the frame on different pathologies than clubfoot. For those reasons, the present Chapter starts with the general description of the Ilizarov frame and then it reviews the literature on the frame, bones and soft tissues analyses.

3.2 The Ilizarov Technique

G. A. Ilizarov developed his method after the Second World War, mainly to correct deformities produced by fractures and to treat the limbs of pre-amputational patients (Simard et al., 1992). As a necessity, he built the frame by using a series of mechanical parts such as wires, rings, rods, bolts and nuts to handle those cases. Nowadays, the frame has different applications. The main uses are bone lengthening, bone regenerations and transportations, corrections of aesthetical problems in the limbs produced by fractures, corrections of bones deformities caused by diseases such as poliomyelitis and others.

The Ilizarov technique consists of the use of an external fixator that enables the correction of orthopaedic pathologies by constant rod adjustments. Nowadays, conventional non-surgical procedures are the primary option to treat clubfoot. The reason is that they are less invasive and cause minor complications, compared to other surgical procedures. However, there is a rate of failure depending on: a) the treatment, b) the patient’s age, c) the severity. Correll and Forth (1996) mentioned that severe clubfoot cannot be treated with traditional procedures. Also, in some cases where, the patient presents circulation problems or skin breakdown, surgeries are not contemplated due to the risk of infections. Also, conventional procedures provide poor results in patients older than eight years of age, but achieve better results if they are used few days after a child’s birth. However, when different treatments have been applied, and outcomes have been poor, non-conventional methods are required.

The Ilizarov method results in a convenient surgical alternative because, compared to other surgical techniques it is less invasive and has the flexibility of allowing different assemblies, depending on the right pathology. One of the main advantages of the fixator is related to its flexibility to perform various adjustments and assemblies depending on
the pathology. Many aspects of the uses of the Ilizarov frame that lead to success or failure are still unknown. However, one of them can be attributed to the lack of a proper and validated methodology to perform adjustments in the frame.

Most of the literature on the Ilizarov frame has mainly studied bone lengthening and fractures stabilisation. Most relevant studies on the frame have focused on analysing the mechanics of independent parts of the fixator, particularly the rings and wires. On the other hand, few studies report results of analysing the interactions of the frame with the limbs. Nevertheless; there is not extensive research on the adjustment procedures and the analysis of the interaction with body tissues (bones, ligaments, tendons, muscles, cartilages) and other soft tissues of the foot.

Proper adjustments of the frame for clubfoot treatment require more complex assemblies than those applied to bone lengthening and fractures. This results from the complexity of the foot and the high number of bones and soft tissues involved in the procedure. It requires correction in three planes, in various stages for the four clubfoot components. For these reasons, nowadays, adjustments of the frame still depend on the experience and criteria of the surgeon.

3.2.1 Historical background of fixation procedures

The history of fixators started a long time before Ilizarov created his famous frame. In the Ilizarov era, the interest on fixators was focused on treating fractures, deformities and on bone lengthening. This is why those applications had a preponderant role in the initial development of fixators. Previous examples of frames have been in Chapter 2 such as the Scarpa’s frame for clubfoot correction. However, the concept of bone distraction took off when Ring carried out a study with puppies in 1954 using external frames (a turnbuckle fixator) to distract their bones and make their bone plates (osteotomy site) grow (Aronson, 2005). Other attempts at bone lengthening application were done by using similar frames. Anderson (1936) used a frame with stirrups to enable the growth of a femur.

Codivilla (2008) studied the lengthening of lower limbs. He carried out a study applying osteotomies to patients where he made bones grow in 26 patients, even if
seizures and other complications were reported. Also, another study conducted by Magnuson in 1913, with animals, investigated the bone growth. Therefore, Magnuson applied his method to 13 humans; one of whom died, and the rest experienced shock (Aronson, 2005). Although his results were not entirely satisfactory, he demonstrated that bone lengthening is possible in humans and that, veins and nerves can tolerate the stresses in the process. This is highly significant because, in clubfoot as other pathologies, there are many soft tissues subjected to stresses during the corrective procedures. Kawamura (1968) carried out a study with animals, demonstrating that bone lengthening reduces blood flow as a function of the growing rate. This way, he defined an adequate lengthening level up to 10% without affecting muscle blood vessels or nerves. Another example of success in bone lengthening was a study described in the literature by Aronson (2005) where, Ombredanne, in 1913, studied the case of paralysis in a child; the femur of the child was elongated by about three centimetres. Those cases illustrate the implications of soft tissues in the corrective procedures, and it opens the questions about the determination of the adjustment criteria of the frame without affecting tissues in the limbs where the frames are applied.

At the same time that Ilizarov method began to be cited and widely applied and recognised by the medical community, Fishbane and Riley (1976), in the United States, practised limb lengthening with an external fixator based on a ring. On the other hand, Wagner (1978) proposed the use of an internal fixator after the distraction process was completed by using a new method based on a unilateral fixator with the capacity of allowing movement. In the current time, some of these fixators and procedures have been redesigned, improved or modified in some mechanical aspects. Examples of these are Taylor’s spatial frame or Hoffman’s method.

### 3.2.2 Medical considerations on the use of the Ilizarov fixator

Depending on the application and the objective of the application of the frame, medical considerations on the fixators are different. For example, in the treatment of fractures, fixators have the primary function of giving stability to the limb (Fragomen et al., 2007). Firstly, in the case of clubfoot, the Ilizarov technique is an option when other conventional methods have failed, so that, the technique is usually an option in cases of
severe or relapsed clubfoot. Assessing the severity of the pathology is relevant to
determine the right procedure. Different scales can support the observational
assessment, for example, Dimeglio, Pirani or Kite’s scales. Usually, patients under
treatment based on the Ilizarov technique have tried other methods before; so, there is
an antecedent of clubfoot treatment. It is always important to consider previous surgical
procedures involving soft tissue releases such as tenotomy, osteotomy and others. In
some clinical cases, infections have been reported at any stage of the proceedings. As a
result, medication, such as antibiotics, is necessary to control infections. Instructions, to
clean the zones in contact with the frame, are needed to avoid infections. There is not
extensive information about the interaction between the materials of the frame and
materials of the human body. However, Ilizarov frame parts are designed with
biocompatible materials (titanium and stainless steel).

In the case of bone regeneration to treat fractures, the consumption of tobacco is
prohibited because it can affect the regenerations of bone tissues. Also, patients are
advised to avoid smoking to reduce the risk of infections in the wire-limb area. On the
other hand, for clubfoot treatment, the prescriptions are similar in those cases where
other surgical procedures are necessary. Studies argue the efficiency of Ilizarov frame in
the correction of clubfoot. Correll and Forth (1996) studied cases of severe clubfoot and
analysed the advantages of Ilizarov technique in the correction of severe, relapsed,
neurological and neglected or recurrent clubfoot cases, based on the good results
obtained after treating 34 patients. They classified patients according to good,
satisfactory or bad results. In the first category, good, implies normal walking after
treatment without presenting discomfort and complaint. The second category,
satisfactory, is indicated when there is still a visible deformity of the foot even if
walking is possible without discomfort and the skin does not present wounds. The last
category, bad, is for cases that show a recurrence of clubfoot after the treatment.
According to 20 cases classified in the range of good results, it is possible to consider
the Ilizarov technique as an excellent option to treat severe clubfoot.

However, the importance of clinical research studies on the basis of good correction
outcomes is due to the controversy between the medical communities on the use of non-
conventional procedures as a first alternative. Another study reporting the result of the
use of the frame is the one directed by El-adly and Mostafa (2009). The authors reported
the results of treating 15 patients. Their study suggests that the Ilizarov procedure is an excellent treatment option in recurrent and severe clubfoot cases. In addition, Grill and Franke (1987) argue that Ilizarov technique is an adequate option to correct severe clubfoot without waiting for the complete skeletal development. This means that it can be implemented to correct clubfoot in children, as well as adults, achieving a high rate of success. Then, invasive surgical methods such as osteotomies or tissue releases can be avoided as the first alternative. Figure 3.1 shows a clubfoot case corrected by the Ilizarov method in adults.

![Figure 3.1 Ilizarov results in an adult case, before and after the procedure (Grill & Franke, 1987)](image)

Other researchers such as Malizos et al. (2008) provided information about cases where soft tissue release procedures were applied simultaneously to the Ilizarov technique, getting good results in adult patients. Another study was reported by Franke et al. (1990). They found good visible outcomes in the profile of the foot, suggesting soft tissues release not to be necessary in all cases. Some of the complications that were reported are oedema (bruises on the skin) on the foot and infections. Bradish and Noor (2000) stated that some of the effects of placing the frame can be infections around the wires but, in general, there is a good response to the application of antibiotics. Other complications, when applying the Ilizarov technique such as cyst in the fifth metatarsal bone, have been reported in the literature (Ganel et al., 1997).
Figure 3.2 shows a clubfoot case in a child during the correction. In clinical applications, the typical adjustment rate is 0.25mm four times a day which is about 1mm per day (Grivas & Magnissalis, 2011). However, there are not numerical studies to validate this adjustment rate.

### 3.2.3 Applications of the Ilizarov Fixator

The Ilizarov technique is used to treat pathologies in different limbs. One of the most recurring applications is the treatment of a fracture, to immobilise the affected limb. Also, it is used to correct the angle of the bone after the bone has been already healed. This method provides fast recuperation after the procedure. Also, it has been tested in fractures of the pelvis, hip, arms, and lower limbs, such as foot and tibia, with a high rate of success. Good average results have been reported in the literature for the treatment of open fractures (Tetsworth & Paley, 1994).

Another frequent use is for bone reconstruction in patients, where the shape of a bone is required to be modified with surgery by an improper assessment, fractures, and so on. Commonly these procedures involve osteotomies to correct the bone's shape, and then
Chapter 3 Review on the study of the Ilizarov frame and the foot tissues

the angles are modified with the Ilizarov technique. This technique is referred to as bone transportation, and it is also used to correct the length of limbs. Lengthening is useful in cases where there is a difference of the longitude of long bones such as femurs, tibias or arms between both limbs. The procedure consists of an osteotomy to separate the bone and creating a gap where new tissues will grow. Then, the Ilizarov frame is placed on the limb by fixing the wires to the bones and rings.

Applications of the frame to non-limb parts of the body have been reported. For example, in the treatment of cervical deformities whose patients presented infections and partial recurrence in some patients Graziano et al. (1993) and mandibular lengthening with no complications to treat mandibular hypoplasia (Klein & Howaldt, 1995). Other important applications have been reported in the literature, for example, to change the aesthetics of bones because of neonatal conditions or illness such as poliomyelitis with minor complications (Kirienko et al., 2003). Also, lengthening is a cosmetic procedure to increase height or to correct the longitude when there is a difference in the longitude of bones in the limbs. Different authors have described the foot reconstruction where, the ilizarov procedure has been undertaken for a variety of conditions (Grant, 1992; De la Huerta, 1994; Paley, 1994). Those include untreated, residual, or recurrent clubfeet in adults, posttraumatic deformity and degenerative joint diseases.

Nevertheless, The ilizarov frame, compared to other fixators, has the advantage of being adjustable to the conditions of different patients. That gives more flexibility to the doctor when placing the frame on a patient with combined pathologies. The current thesis is focused on the analysis of the clubfoot correction using the ilizarov technique.

3.3 Design of the Ilizarov frame

The ilizarov frame is an external mechanical fixator that constitutes a rigid structure, once it is attached to the limb to be corrected. The main parts of the frame are: a) rings, b) rods, c) wires, and d) connectors. The wires are the only elements of the frame to be in contact with the body. Their primary function is to connect the limb to the rings of the frame by introducing the wires into the bone and connecting the ends of the wires

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ends to the rings. Different options for the arrangement of the wires can be set up; that depends on a) the number of wires into the bone, b) the angles between wires c) the thickness of the wire. In this Chapter, studies on the effect of these variables on the assembly and their deployment are described. Figure 3.3 displays an example of the interaction among wires (a) and rings, wires and bones (b).

The Ilizarov frame has a broad range of clinical applications. Compared to other fixators such as Taylor’s spatial frame, the Ilizarov frame can achieve very versatile designs with different variations in the assembly. This way, it can be used to produce entirely different assemblies, depending on the limb the frame is placed on and the pathology. The dimensions of their parts vary depending on: a) the size of every patient, b) the requirements of the pathology, c) the limb to be treated.

Figure 3.3 a) Wires into the talus, and b) wires linking the bones to the half rings (Kirienko et al., 2003)
Figure 3.4 shows some of the most representative parts of the frame such as rings, rods, bolts, nuts, hinges, T-shape connectors, etc. However, there could be other special connectors to build complex assemblies.

The manufacturer of the Ilizarov parts, Smith & Nephew (2006), offers parts with different dimensions to provide versatility in the assemblies. For example, the internal diameter of half rings varies from 80mm to 240mm. The diameters of the wires are 1.5mm and 1.8mm with different lengths, M6 screwed rods with lengths varying from 30mm to 400mm. Also, the company manufactures bolts, nuts, hinges, universal joints, washers and other connectors to according to the dimension of the other components.

Depending on the pathology, there can be more or fewer components, as well as special connectors and parts as seen in their materials booklet. For example, they provide documents with general suggestions and advice for the assembly of specific pathologies such as tibio-talocalcaneal arthrodesis (Smith & Nephew, 2010). This availability of parts with different dimensions in the market provides a powerful tool for: a) achieving complex assemblies adjusted to the necessities of treatment for every specific patient, b)
enabling the analysis of the mechanical deployment of isolated parts or particular assemblies with different connectors and parts.

In the case of clubfoot, the frame is designed to treat relapsed or severe clubfoot (Correll & Forth, 1996; Malizos et al., 2008). Then, the assembly for this pathology can be divided into two sections: 1) The tibiofibular upper assembly, b) the foot and ankle lower assembly. The description of these two sections is relevant because identifying how physically they work, enables establishing a reliable analysis. In a typical clubfoot assembly, the first section consists of two full rings connected to the tibia by four rods. The second section consists of two half rings and six main rods. However, there can be more or less in the number of parts depending on the pathology. The first half ring is placed in the posterior bones of the foot. Commonly, it is attached to the calcaneus or talus through wires. The second ring is placed over the phalanges in the anterior foot.

The main difference between the upper and lower section of the frame for clubfoot treatment is that the upper one has minor adjustments during the treatment. This is because it has the function to maintain the full frame rigid and stable on the limb. In contrast, the lower section is subjected to gradual changes in the assembly as rods are adjusted in order to provide correction. The main rods of this section are constantly adjusted to correct the equinus, varus, adductus and cavus clubfoot components. As a result of the correction, the bones modify their positions in different directions.

Depending on the instructions of the surgeon it is common to treat first the varus and equinus components as they amend the position of the bones in the ankle. As a result, the foot’s plantar fascia is closer to its natural position. The final correction is achieved by treating the adduction and the cavus deformity. Figure 3.5 shows the two sections of the frame for clubfoot correction.
The foot and ankle lower assembly requires, from time to time, subsequent rod adjustments. Usually, the adjustment is made every day by displacing about 1mm per day, until achieving the expected final foot position. However, during the correction period, the parts of both sections are fully connected, resulting in a rigid structure. On
the other hand, the second section is attached to the foot and ankle which contains the bones to be repositioned. For those reasons, the best first approach to analyse the frame is to consider the stresses instead of the kinematics. This is because: a) every variation in the pathology requires a different assembly, b) there could be redundancies if analysed as a kinematical assembly as it is not symmetric, d) the frame is designed to work as a structure c) the most critical frame deployment from a design perspective is during the correction (when the pins and connectors are fully tied). The relevance of a) is highly important because even if the frame is analysed as a kinematical assembly, the kinematics would be entirely different for other assembly variations. On the other hand, the Taylor’s spatial frame compared to the Ilizarov frame provides the possibility to perform more accurate arrangements but, less flexibility to achieve complex assemblies.

Figure 3.6 Frontal view of the Ilizarov frame in a clubfoot position
Figure 3.6 shows an assembly previously used in a patient by an orthopaedic surgeon at the Manchester Clinical Hospital. A sawbones model was placed inside the frame to represent the pathology. In contrast to Figure 3.6, Figure 3.5 shows the assembly when the foot is fully corrected. Both Figures display variations in the assembly and a different number of parts, as design depends on the pathology. Also, Figure 3.6 shows a slightly bent frontal rod which was produced in the rod during the period of correction. The understanding of the stresses in the frame is part is part of the objectives of this thesis.

The adjustment of the Ilizarov frame can be complicated depending on the exact pathology of every patient. This is because, compared to the correction of other pathologies, clubfoot involves four components to be corrected in different directions. Thus, the design of the frame is able to correct deformities of the foot in the tree axial planes of the human body (sagittal frontal and transversal). The relative positions and relative orientations of the different elements of the foot in those planes are used to describe the different deformities. In addition, the degree of the angles of deviation of the foot from those planes, determines the severity.

*Figure 3.7 the most common adjustments of the frame for clubfoot.* (Kirienko et al., 2003)
Figure 3.7 shows the possible adjustments of the frame to correct cavus, varus, equinus and adductus components. Shortening rods 1 and 2 enables to correct equinus foot. When lengthening rod 3, it is possible to correct cavus deformity in clubfoot. Rods 4 and 5 are disposed to correct the varus deformity in the hind foot by means of the lengthening of rod 4 and shortening of rod 5. Adductus deformity is corrected by modifying the longitude of rods 1, 2 and 4. In this case, the angle of the two half rings will correct it.

The Ilizarov technique usually does not involve complicated surgical procedures for the clubfoot treatment such as other surgical methods but, in some severe cases, soft tissue release or bone osteotomies are required. This can involve additional rings and rods but this depends on the conditions of the patient.

Some important parameters must be considered for the use of external fixators. In the case of those which use rings such as the Ilizarov fixator, the rigidity of the fixator is crucial in the process of correction. For those reasons, Lucas et al. (1999) state some variables that affect the rigidity of the fixation. These are:

- The number of pins, which are necessary to fix the bone to the frame.
- Pin diameter
- Distance from the ring to the bone.
- Number of rods
- Materials of the frame components.

In the case of clubfoot, the main variables to consider for achieving a good frame deployment are:

- Tension levels of fixing the wires
- Daily adjustment frequency
- Wire dimensions
- The position of the wires in the foot and ankle.
- Number of wires
- Angle between wires
In general, those factors affect the proper application of the frame, and that is reflected in the outcomes. Some mechanical aspects to consider are based on the dimensions of the elements of the frame such as the longitude of rods which modifies the moment. The size of rings and the distance between bone and connectors affects directly the rigidity of the frame. Some studies related to the mechanics of the frame’s design are presented in this Chapter. Some of those parameters are analysed in the following section.

Regarding the procedures, there is still a range of failure attributed to the lack of research on the improvement of the adjustment procedures. This can result in difficulties in the process of correction and side effects, e.g. possible infections. These infections can be attributed to pin track (Franke et al., 1990). For these reasons, it is relevant that the analysis of the frame considers: a) the isolated frame sections and b) the interaction of the frame with the foot tissues. These two topics provide a vast range of studies to contribute to the frame adjustment procedures to achieve the best possible results. Finally, it is important to emphasise that there is not a single design of the Ilizarov frame to be applied to all patients and pathologies. There could be variants using different parts and connectors. The literature provides suggestions on possible assemblies for some pathologies and advice in the adjustment. However, there is still not a validated literature on the adjustment procedures. As stated before, it still depends on the surgeon’s experience to date, resulting in the possible range of failures of the frame.

Figure 3.8 shows the adjustment of the frame to correct clubfoot deformity. Gradual adjustments in the length of the rods and rings modify the position of the foot which first looks like Figure 3.8 (a) in clubfoot and later in a normal foot like in Figure 3.8 (b). In some cases, the frame has additional wires to correct toes deformities when they are affected by clubfoot condition.
3.4 Literature review on the analysis of the Ilizarov fixator

Since the 1950’s when Doctor Ilizarov developed and started to apply his technique in different cases, mainly those which involved fractures and correction of deformities, the Ilizarov frame has obtained popularity in various countries. This is because of its flexibility to be applied in different pathologies in orthopaedics. Results of clinical studies reported in the literature on different applications support the success of this technique. While the side effects, as well as some of the features of the frame elements, have been analysed over the years, some features are still being studied at the present. In the case of clubfoot correction, Ilizarov frame has been applied in different cases where age, gender, ethnicity and clubfoot severity varies among patients. Although general results reported in the literature, reflect the success of the technique, a considerable range of relapsed clubfoot has been reported. However, there is still not a standardized procedure to adjust the frame during the treatment for clubfoot. It is important to emphasise that few numerical analysis has been made on the frame and its interaction with the body. The majority of the analyses reported in the literature on the frame have focused on the Ilizarov frame elements and other applications that are different from clubfoot. Foot and ankle modelling with the frame under different foot conditions have
not been deeply analysed because of the complexity of lower limbs and the complexity to adjust the frame around the foot and ankle.

The frame design enables a huge flexibility to be obtained when the frame is applied to different pathologies such as deformity corrections, fractures and else. The mechanical properties of the elements of the frame have been examined in various studies. For example Watson et al. (2000) studied the behaviour of the fixator considering the stiffness, rotation and torsion of its elements, as well as the frame stability to avoid damage in the tissues in contact with the fixator (Gasser et al., 1990; Orbay et al., 1992).

The design of the frame determines the distribution of forces interaction between the frame and the limb where the frame is placed. Hence, the distribution of forces depends on the geometry, materials, elements of the frame and size, just to mention some variables. Watson et al. (2000) describe the characteristics of an appropriate fixator, which has sufficient stiffness to avoid rotation or torsion, a low rate of damage to the tissues in contact with the frame and the necessary stability of the elements of the frame so that the frame can be used to complete the treatment (Gasser et al., 1990; Orbay et al., 1992).

Some of the most analysed elements of the Ilizarov fixator are the wires and rings. This is because they have a preponderant role in the stability of the frame. Also, rings and wires have the purpose of distributing the stress along the frame structure by keeping wires tensioned to stabilise the fixator. Variables such as materials or dimensions have been analysed by different researchers (Paley & Testworth, 1993; Bronson et al., 1998; Watson et al., 2000). However, the limited displacement of the bones in the bone-wire interaction has been suggested to speed healing in patients (Ilizarov, 1989). This is crucial because the application of the frame involves the interaction with the body. For that reason, the effect of the frame on the body is of importance.

In general terms, the rings have two specific functions: to distribute the stress along the structure and to keep the wires tensioned to stabilise the fixator. The variables that can influence in the mechanical properties of the ring are the size, the material and if rings are segmented (half rings) or full rings (Watson et al., 2000). Some studies (Paley & Testsworth, 1993; Bronson et al., 1998) have found that reducing the dimensions of the ring causes the stiffness of the frame to increase.
Other studies (Paley & Testsworth, 1993; Podolsky et al., 1993) suggest that one of the variables that determine stiffness in the frame is the position of the wires and that the frame stiffness increases when the wires are placed off-centre. Hence it can be determined by diverse variables such as yield of wire, diameter, load, pre-tension, position and angle of the wires between each other, number of wires and size of rings, just to mention some of the most relevant variables reported in the literature (Podolsky et al., 1993; Bronson et al. 1998;). Diameter can vary from 1.5 to 2.0mm according to the studies which support its stability and necessary stiffness to avoid failures or ruptures (Aronson & Harp, 1992; Calhoun et al., 1992; Podolsky et al., 1993).

On the rings, Zhang and Ojadiji (2014) conducted a study to analyse different variables that affect the behaviour of the rings such as the material, the ring diameter or the deformation of the ring. This was based on the assumptions from the literature where Nikonovas and Harison (2005) predicted the linear behaviour of the frame stiffness as a function of the number of wires. Gasser et al. (1990) found that the ring diameter affects the stiffness of the ring which is increased 70% by reducing the diameter 4cms. This finding of the role of the diameter was previously described by studies (Paley & Testworth, 1993; Bronson et al., 1998). In order to investigate those variables, Zhang and Oyadiji (2014) performed a finite element analysis using a double ring structure with 2 wires and a cylinder to simulate the bone(10mm of length and 6mm inner diameter). They analysed rings with different diameters (150mm, 180mm, 200 and 240), and different wire lengths (180, 210, 230 and 270mm) at 1.8mm thickness. In addition they performed a mesh analysis comparing different element types to verify the model, finding that the element type C3D20 on the Abaqus FEA software favours a faster enough accurate analysis. The methodology of their study consisted on fixing the wire angles at 0, 30, 60 and 90 degrees and applying a pre-tension load of 1275N in the wires. Then, they applied 1000N over the upper surface of the bone. Zhang and Oyadiji (2014) found that the material of the rings has a major role when the rings are at 90° than at 0° and also that the stiffness of the frame varies at different wire angles but, this variation can be attributed to the deformation of the ring as shown in Figure 3.9.
On the other hand, the principal function of wires in the frame is to fix the frame to the limb. There are studies on the analysis of the variation of the angle between wires (Aronson & Harp, 1992; Orbay et al., 1992). Paley and Testworth (1993) determined that the most appropriate angle between wires is 90 degrees, in order to provide stability to the frame in flexion. Figure 3.10 shows different wire arrangements.
Wires have been proved to have a significant role in the stabilisation of the frame. Orbay et al. (1992) carried out an experiment to analyse the stability of the Ilizarov frame subjected to different wire configurations. The researchers replicated a bone employing a hollow PVC plastic tube, with a 4mm wall thickness. They analysed 1.8mm and 1.5mm olive wires. They attached the ring to the simulated bone by using pre-tensioned wires loaded by 90Kgf. The two modes they tested were a model with a single ring and with two rings with 2 crossed wires with wire angles varying in steps of 15 degrees until 75 degrees. They found that the rigidity of the frame depended on the number of wires. Also, the rigidity decreased when the angles were less than to 60 degrees. In addition, a third wire reduced bending and increased the stability of the frame.

In another research, Hillard et al. (1998) conducted a study where they analysed the plastic deformation of the Ilizarov frame wires finding that reducing the tension in wires reduces the stiffness and promotes shear forces in the frame. It can promote infections or other side effects and problems in the process of healing with the frame. Dong et al. (2005) evaluated tension wires in order to provide a method of assessment. They found a correlation between tension and deflection in wires where the distance between the bone and clamps to subject the wires is the variable that affects the tension-deflection relation.

On the other hand, Nikonovas and Harrison (2005) carried out a study that evaluated the deflection and stiffness of wires in the Ilizarov frame through a simple numerical model applying torsional loads as well as axial loads. The authors modelled a 1.8mm thickness wire with 800N axial load and 32Nm for angular stiffness and a 30 mm diameter cylindrical bone, over different wire pre-tension loads as shown in Figure 3.11 a) and b). From the medical perspective, the stiffness of the frame components and the general frame assembly are crucial, because micro-motion wires promote healing in the treatment of bone distraction. Results show the relationship between stiffness of the wire-bone-ring segments as a function of the numbers of wires to fix the ring to the bone. This result in a linear relationship in both cases, that is in the axial and torsional loading cases where the stiffness increases as a function of the number of wires.
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Figure 3.11  Stiffness as a function of the number of wires. (Nikonovas & Harrison, 2005)
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Figure 3.11 (a) shows the relation between the number of wires and the axial stiffness in the wire-bone-ring segments. Figure 3.11 (b), shows the same results but for angular stiffness of the same segment (wire-bone-ring). The Figure shows a linear behaviour of the wire-bone-ring stiffness in both cases as a function of the number of wires. A higher number of wires favour the increase of the stiffness values of the frame, favouring the reduction of plastic deformations in the frame wires. The importance of this study comes from the hypothesis that the micro-motion of the fine wires can be beneficial in cases that involve bone healing due to the flexibility of the wires. In clubfoot, it would be interesting to analyse the role of the stiffness of wires in the Ilizarov frame as a function of the results in clinical outcomes for the correction of clubfoot. This is because in clubfoot compared with bone lengthening or fracture cases, the tibia is intact but soft tissues transmit the torsional loads during clubfoot correction. As most of the analyses about the frame have been performed for other pathologies than clubfoot, investigating the role of the wire in the clubfoot correction for adults and kids may provide information to improve the current procedures.

Those previous studies suggest that the effects of pre-tension are important to be deeply studied because they can affect the bone-wire area. Thus, they can affect the body tissues. Zhang (2004) studied one isolated wire that was analysed with the Finite Element Method, considering a plastic non-linear elastic analysis. The findings suggest that due to the non-linearity of the wires, pre-tension reduces plastic deformation but increases hardening and yielding. Figure 3.12 shows the nonlinear behaviour of wires as a function of pre-tension.

![Deflexion curves (Zhang, 2004)](image)

Figure 3.12 Deflexion curves (Zhang, 2004)
Another study carried out by Board et al. (2007) investigated the pressure levels between wires and bones. Comparing with other studies, they analysed the interaction of the element of the frame and the bone. Watson et al. (2005) carried out an investigation to determine the accuracy of wires subjection system; where they performed five tests and found differences between tests with a deviation of 4.9%. Bronson et al. (1998) investigated the variables of the frame that affect the stability of bones and they found that those parameters are mainly ring diameter, wire angle, the distance between the frame and the bone, and ring position. Those variables affect directly the torsional and axial stiffness.

Watson et al. (2007) analysed the stiffness of a frame considering different configurations. To get that goal, a finite element study was carried out using the elements of the frame (rods, wires, rings and threaded rods). Results from FEM were compared with experimental results. In addition, the behaviour of K-wires have been studies by Zamani and Oyadiji (2010); the lateral deflection of wires was analysed. They constructed a 3D model using a hollow cylinder as a bone whose mechanical properties were: modulus of elasticity of 200GPa and Poisson ratio of 0.3. On the other hand, the K- wires were modelled as cylinders of 1.8mm diameter. The model did not consider friction conditions and the wires we analysed at: a) different pre-tension levels (490 MPa at minimum and 1275MPa at maximum), and b) at different angles between wires (45 and 90 degrees). The results suggest that wires show a non-linear behaviour as a function of pre-tension rate where nonlinearity is higher as pre-tension in the wires reduces. Also, they showed that the K-wire deflection behaviour does not depend on the angle between wires. Figure 3.13 shows the finite element analysis of K-wires modelled as cylinders in two different angles between each other (45° and 90°).
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Figure 3.13 Finite Element Analysis of the K-wires a) 90 deg between each other, b) 45 degrees (Zamani & Oyadiji, 2010)

Figure 3.14 Lateral deflexion of K-wires at different loading ranges (Zamani & Oyadiji, 2010)

Figure 3.14 shows the non-linear behaviour of the K-wires as a function of the lateral deflection due to low pre-tension rates where, F=0 presents higher deflection compared to those with the maximum tested pre-tension, F=1275N. Zamani and Oyadiji’s (2010) findings are in agreement with a study performed by Zhang (2004) where he studied the nonlinearity of external fixators. He concluded that pretention benefits the stiffness in the fixator but reduces the elasticity of the wires. These results show a non-linear
behaviour of non-pre-tension wires as a function of gradual increment of displacement by a higher deflection. In clinical applications, these results are relevant as they affect the stability of the frame and its rigidity during the correction. However, it opens the question about the stresses caused in the bone-wire area for clubfoot correction as a function of the pre-tension and the deflection rates, in adults and babies.

Other elements considered in the design of the frame are rods and connectors which are also important to be analysed. The function of these elements is to align the limbs in order to correct its angle. These elements enable gradual modifications of the deformity by means of little frequent adjustments of the frame. It is necessary to investigate the correct adjustments of the frame due to the pathology of every patient.

There are experimental studies such as that of Davidson et al. (2003) that analysed the bolts and components to hold the wires and the methods to tension them. Their conclusions suggest that Russian design of bolts has better performance when bolt twisting is the method to tension the wire. Figure 3.15 (a) shows the ring wire interaction and (b) and (c), the comparison between two different bolts used to assemble the frame.

![Figure 3.15](image)

*Figure 3.15 a) ring-wire-bolt, b) bolt 1, c) bolts 2 (Davidson et al., 2003)*

Many studies have analysed the independent parts of the frame, excluding the interaction with the limb. On the other hand, Board et al. (2007) conducted a study to analyse the interaction between bones and wires by measuring the pressure in the bone-wire area. They designed an experimental model to compare two different ways to fix the ring to the bones. The first is the use of K-wires. The second is the use of half pins technique. For the first experimental test, they tested wires of 1.5mm to 2.0mm
diameter. The wires were tested at different depth surfaces from 0.5mm till 2.5 mm with increments of 0.5mm. The tension of wires was measured using strain gauges at 1200N. Then, they inserted the wire inside polyurethane foam with a density of 200kg m$^{-3}$ to simulate the bone. The load was applied at different pressures from 0.19MPa to 96Mpa. On the other hand, the pressure distribution in the half-pin model was tested with a screw of 6mm of diameter and 30mm of length. The results suggest significant differences in the pressure distributions between both techniques being the higher pressure in the wire-bone area less than 2Mpa level in the bone-wire interaction area compared to pressures higher than 20Mpa with the half-pin technique. Board et al. (2007) state that, this is the possible explanation of a lower loosening rate of wires compare to the half-pin technique.

Figure 3.16 Vertical displacements analysis using a Finite Element Model. (Nielsen et al., 2005)

Some finite element method studies have been done on the interaction of the frame with the human body and its influence on the treatments. Nielsen et al. (2005) analysed the rigidity of the frame in patients with arthritis because it has well argument that the stiffness of the fixator determines the results after the treatment. As it is shown by other studies stiffness of the frame is affected by the distance between the rings and the tibia.
For this study, employing the finite element method, the displacement in the frame was analysed and results are shown in Figure 3.16. This 2D model is the only one to date in the literature on the analysis in pathologies of the foot and ankle.

Results of previous researches help to improve the current procedures in the clinical applications. These findings must be considered because advantages in the stability of the frame may provide corresponding advantages, in particular, clinical cases during the correction. On one hand, Ilizarov (1989) suggested that a limited displacement of the bone in the wire-bone interaction promotes healing. Zamani and Oyadiji (2010), and Zhang (2004) predicted a non-linear behaviour of the K-wires as a function of the pre-tension. This means higher deflection which represents more flexibility of movement in the wires with lower pre-tension values but at the same time, it represents less stability. Nikonovas and Harrison (2005) showed that the frame presents higher stiffness as a function of the number of wires. This opens up the question about the effects of the number of wires (by increasing or reducing the wire-bone contact area) on the bone when patients apply dynamic loads. An example is when walking as it could promote displacement of the bone. This is the result of the application of the load by the weight of the body and the lower flexibility of wires. However, the clubfoot procedures have not yet been thoroughly investigated resulting in a range of failure of the frame.

3.5 Literature review on the analysis of the foot tissues

3.5.1 Bones

Modelling of bones has been important in medical fields such orthopaedics, to provide information about the behaviour of those tissues in normal and abnormal conditions, in order to support the assessment of patients. Many works on bone modelling to analyse different limbs have been reported in the literature. The approach to this analysis has changed with the passage of time and different studies have been carried out in order to obtain bones features such as mechanical properties. The studies have also included analysis of bones fractures, as well understanding the behaviour of bones in different situations, usually medical conditions which are defined by diverse problems such as
fractures, deformations, osteoporosis, arthritis or any other state which modifies their normal functions. Other factors that can affect bones are nutrition, ageing and different loading conditions have been analysed in different medical cases. Work on modelling has kept up pace with the development of computational resources and increasing the power of data processing. Numerical analysis with methods such as Finite Element has been applied in different fields, including mechanics and biomechanical cases.

The difference between biological materials and non-biological materials other ones is that the properties of biological materials change according to different variables such as the age of the person, sex, location of the bones, loads applied, hormonal condition and nutritional habits, just to mention some factors. For these reasons, spongy bones tend to have a lower elasticity modulus. In adults, bones are usually harder than in children due to the process of growing. Some tests have been done in order to obtain the properties of bones, even though they are biological tissues which have water in their cells. Making an essay to get their properties in a lively bone comparing with a dead bone can change their properties. Other external factors can affect the mechanical properties of bones, such as the dietary habits which can determine the loss or gain of calcium. The age has a preponderant role in these conditions. Stress applied to bones provides the basis for rehabilitation and there are different studies to determine the stress-strain curves of different bones of the body. Due to the change of the stress-strain curves and mechanical properties mechanical in the interior of the bone, different properties are defined for cortical and trabecular bones

Minster (2003) used a viscoelastic model of cortical bones in order to know their deformation due to load response. He compared his parametric time functions with experimental data obtained in the literature.

The constitution of bones depends on the stress conditions to which they have been subjected. This was shown in a study from the literature described by (Fung, 1990). Also, there are studies where, the mechanical properties of bones have been represented analytically. For example, Fung (1990) reported that in 1976, Hudgens developed a model based on the constitutive equations in order to obtain the stress-strain curves of bones. The modulus of elasticity of the tibia was reported to be about 18.5 GPa and 17.6 GPa for femur (Fung, 1990).
In another study conducted by Taylor et al. (2002) employing CT scans taken from cadaveric bones, they created the bones biometry to be analysed as well they determined the natural frequencies of the bones through modal analysis. As mentioned before, some factors such as loading, nutrition and ageing affect the mechanical properties of bones so that; there is a time-dependency of their mechanical properties. Beaupre et al. (1990), investigate that time dependence in an adult bone of the proximal femur in order to get the bone density along the specimen. He discovered that load increases the density of the bone. Other studies evaluate the differences in mass bone loss in normal ageing comparing with specific conditions such an osteoporosis (Morley & Flaherty, 2002).

Computational models have been proved to be a reliable solution to analyse the mechanical behaviour of human biomechanical structures such as bones and soft tissues. This is relevant for the analysis of living tissues because experimental tests require consent for using cadaveric donated bones. However, numerical models can provide a reliable approach when the variables and methodology are adequate. For example, Iaquinto and Wayne (2010) conducted a study to analyse the lower limb focusing on the leg, foot and ankle. The researchers obtained the foot geometries from CT scans taken every 0.6mm and performed the assembly of bones using Solidworks. The geometries of the ligaments were modelled using CosmosMotion elements. Finally, they compared their results with those reported in the literature on cadaveric experimental tests. Their findings suggest that plantar facia arch, plantar ligaments and spring ligament in the foot are the principal structures responsible for providing stability in the foot plantar fascia.

Figure 3.17 shows the modelling of the plantar fascia in the foot. This shows that modelling bones using CT scan data provides a reliable solution to create bone geometries. Creating bone geometries based on patients compared to idealising the geometries using symmetrical objects such as cylinders or spheres, has contributed to the accuracy of models. Figure 3.17 a) describes the load application for the FE analysis performed by Iaquinto and Wayne (2010) where, the arrow represents the direction and the point of load. Figure 3.17 b) shows the modelled ligaments in the plantar fascia, described in Table 3.1
From the modelling perspective, modelling wires as 3D cylinders offers a reliable possibility to analyse the behaviour of wires under different conditions.

### 3.5.2 FE foot modelling

The study of soft tissues has been important in order to know the complete behaviour of limbs. In some cases, the bone analysis is not enough because some limbs involve the interactions of different elements, such as muscles, ligaments, tendons, cartilage or any other soft tissues.
It is important to say that bones are the elements that give support to the structures in the body and they have a relatively high modulus of elasticity and they tend to be more fragile than ductile. On the other hand, muscles, ligaments and tendons have different behaviour from another but in general, they are softer and more flexible compared to bones. They enable the movement of the body and give support to limbs. Due to the properties of the soft tissues, modelling tends to be more complicated because of its viscoelastic behaviour and the assumptions to reduce the model trend to be more complex as well. The methods to generate the geometries are sometimes less conventional and require more time.

Mkandawire et al. (2005) carried out a study on the morphometry of the ligaments of the foot using a fracture technique. The tests were conducted on cadaveric samples and the study consisted of harvesting ligaments from the samples and measurements of width and thickness were taken so that cross-sectional area could be calculated. The Freeze-fracture method was applied to increase the accuracy of the measurements and compared with the measurements using callipers a derivation of about 35% was obtained. The results showed that the cross-section area obtained ranged between 21.3 to 170 mm².

One of the main differences between normal feet and clubfeet is the change of soft tissue stiffness and its length rather than deformations in bones. It is relevant to highlight that stiffness in soft tissues surrounding the foot is completely different from normal feet. There are not many studies on the stiffness and properties of soft tissues in clubfoot conditions that have been carried out.

A model developed by Silvestri and Ray (2009) shows a good approach to model bones and other tissues such as ligaments and muscles in the knee-thigh-hip junctions to investigate the mechanical behaviour of those elements when injured. The geometry of the model described by Silvestri and Ray (2009) was based on a previous model which contains foot, ankle, femur, pelvis and knee and it was verified by experimental studies in cadavers. Material properties of ligaments were obtained from tests of porcine specimens which were assumed to have a similar mechanical behaviour. Because ligaments behave as one-dimensional discrete elements, they were modelled using non-linear spring elements. Figure 3.18, shows a model of the leg with ligaments.
In the human body, mechanical properties in every tissue changes, so that mechanical properties of foot elements are different from any other limb and change due to certain medical conditions.

Figure 3.18 shows muscles and ligaments modelled as spring elements and attached to the bones of the lower limb. Spring elements have been used to model these tissues in the literature. Figure 3.19 shows another example of an FE model of the plantar fascia in the foot where, the main ligaments were modelled using spring elements. Figure 3.19 (A) and (B) show the bones, cartilages in yellow and spring elements as ligaments. Figure 3.20 shows the stress patterns in the foot phalanges.
In another study, Funk et al. (2000) presented an approach to the modelling of viscoelastic properties of the main ligaments of ankle-foot. Figure 3.21 shows some of the most important ligaments in the ankle joint.

**Figure 3.20** Stress on foot phalanges with ligaments. (Garcia-Gonzalez et al., 2009)

**Figure 3.21** Most relevant ligaments in foot-ankle joint (Funk et al., 2000)
Chapter 3 Review on the study of the Ilizarov frame and the foot tissues

Cartilage is an important tissue to be considered because in children, it is found in a big amount and it has been referred as a viscoelastic material because of its high porosity and its properties of a fluid (Fung, 1990).

Ligaments, tendons and muscles have an important role in the proper foot functions. Achilles tendon enables locomotion and its mechanical properties where described by Wren et al. (2001) whose modulus of elasticity, was identified to be 822 MPa, which is close to the values of other tendons in the body.

Wei et al. (2011) developed a 3D Model to analyse ankle injuries. They modelled the ligaments as spring elements and bones taken from CT scans and processed by the software Mimics.

Figure 3.22 3D model of the foot with spring elements as ligaments (Wei et al., 2011)

Figure 3.22 shows the model with bones as 3d elements taken from CT scans and spring elements to model some of the most important ligaments. Also, Wei et al. (2011), provide a table with the reference values for the ligaments included in their model. Figure 3.23, contains those values with similar values of some of the ligaments, reported by Iaquinto and Wayne (2010).
Chapter 3 Review on the study of the Ilizarov frame and the foot tissues

![Figure 3.23 Ligaments stiffness (Wei et al., 2011)](image)

The information about the soft tissues suggests that analyses carried out on pathologies must consider the differences in the mechanical properties of tissues as a function of different aspects such as age and the behaviour of the limbs. Also, the soft tissues involved in the foot anatomy have an important role for the analysis aimed at investigating the mechanical behaviour of the foot under different pathologies. Chapter 5 aims to investigate the mechanical behaviour of the talus in clubfoot, due to its important role to preserve the foot stability in normal feet and the variety of soft tissues (ligaments) connecting the talus with other tissues.

3.6 Summary

Biomechanics is a multidisciplinary area that involves mechanical engineering applied to biological subjects, mainly humans, in order to provide solutions to medical
pathologies and a better understanding of the mechanical behaviour of the body. This is attained by means of the use of the available technological tools to date to conduct assessments, analyses and researches. These investigations comprehend a) the current treatments, b) developing novel solutions to problems in orthopaedics and other related medical areas, and c) performing basic and applied research to understand the mechanical behaviour of the body in normal and pathological conditions. As a multidisciplinary project, it requires, on the one hand, a clear understanding of the medical aspects involving the clubfoot pathology as described in Chapter 2 and on the other hand, a broad knowledge of the mechanical behaviour of the foot tissues and the Ilizarov frame. Chapter 3 covers the related review of the mechanical behaviour of foot tissues and the Ilizarov frame. This is important in order to define the variables for the current models and current modelling techniques, identifying the gaps in the literature and defining the assumptions to enable the development of the biomechanical models for proper analysis of the clubfoot pathology.

The foot is a complex biomechanical structure. As a result, the models to investigate the foot are commonly big in size and require long analyses times. The model reductions or simplifications are essential to perform adequate analyses. On the other hand, some gaps in the literature justify the objectives of the current thesis. The most significant aspects of this review are described as follows:

- There are few analyses on the Ilizarov frame applied to the foot and ankle. The majority of the mechanical analyses in the literature have been conducted to understand a) the mechanical behaviour of independent components of the frame; b) the frame applied to the tibia and fibula, for bone lengthening or fracture treatments.
- There are very few analyses of the foot in clubfoot conditions. The differences of stiffness and mechanical properties of a normal foot compared to a clubfoot determine a significant gap for a better understanding of clubfoot.
- The current modelling techniques described in the literature enable to define the modelling techniques to investigate the Ilizarov frame applied to clubfoot and the role of the talus in clubfoot of babies.
• The current few models in the literature on the Ilizarov frame applied to the foot are 2D models. The present work represents an effort to provide a more realistic and accurate analyses compared to the real medical application.

• The literature on the mechanical properties of the foot tissues in babies is limited. Consequently, the literature on the tissues in clubfoot babies is even more reduced.

• Understanding the mechanical behaviour of the foot tissues in babies is important because: a) commonly, the first medical treatments to correct clubfoot are performed after birth, b) relapsed clubfoot results from the failure of treatments in childhood, and c) the literature reports changes in the foot shape after the treatment by conventional procedures. The importance lays in the fact that further pathologies can be developed because of an improper clubfoot correction as a result of the limited literature and analyses to improve the current treatments.

• The literature reports different statistics on the success and failure rates of different treatments. These studies encourage the interest to study the current corrective procedures for clubfoot in order to develop better procedures and, thereby, increase the success rate.

• The review of the historical background of the frame and its applications enables the identification of the evolution of the frame. Thus, the advantages and disadvantages of the frame, compared to other corrective procedures for clubfoot, can be established. This also enables to distinguish the range of applications of the Ilizarov technique, the scenarios where it can be used, and its advantages compared to other procedures.

• To date, no 3D numerical models have been reported about the utilisation of the Ilizarov fixator applied to this pathology neither in children nor adults. Creating a numerical model to analyse the Ilizarov fixator applied to clubfoot or talipes equinovarus provides information to surgeons to improve the outcomes after the procedure.
4.1 Introduction

Computer-Aided Design (CAD) models are the starting point to perform a finite element analysis because they provide the geometries to be analysed. Furthermore, CAD models are the first step to determine the philosophy in the analysis. Thus, the decision of performing a 2D or 3D analysis is taken at the beginning of the study. This can depend on the particular conditions of the problem to be analysed and the established criteria for the analysis. In the case of the analysis of living tissues such as bones, CAD models required to perform the FE analysis, are not generated by conventional methods and software. The reason is that bones are not symmetrical, and their geometries have different depths and a different cross-sectional area along the geometry. Bones, compared to most common manufacturing parts in the industry, are difficult to create with conventional CAD software. Techniques such as X-Ray Computed Tomography (CT scans), Magnetic Resonance Imaging (MRI) or the use of Scan cameras are some of the most common procedures to create the geometry of a bone. However, additional image processing procedures are required to be applied to obtain solid geometries to be subsequently processed by a Finite Element Software.

Usually, complicated analyses are initiated from simple models to approximate the behaviour of the case study. This implies: a) a deeper understanding of the case study, b) reduction of the possibilities of providing wrong paths in the construction of further complicated models, c) basic approximations that can provide a reliable approach to complex analyses. Additionally, sometimes, basic approaches provide relevant information to be applied in subsequent models. For those reasons, the present Chapter
Chapter 4 Procedures for the development of solid models of bones and the Ilizarov frame components

contains the detailed description of the procedures to generate the CAD designs of the bones of the foot, the components of the Ilizarov Frame and the assembly of the models. Furthermore, this Chapter describes the basic background on the CT scan image generation and image processing techniques for the models analysed, emphasising the relationship between the CAD models and the Finite Element Analysis.

4.2 Overview of biomechanical modelling

Bones are difficult to model based on conventional CAD design software because bones are asymmetric with a different cross-section area along the bone. In some mechanical cases, reduced and simplified models produce high accuracy. However, to increase the accuracy of biomechanical models, it is better to build the CAD models geometrically similar to the real tissues although, model simplifications are usually necessary to reduce computation time. In some cases, analyses are so complex that reductions provide a better approach. It depends on the considerations of the researcher. To date, there are dedicated techniques to acquire bones geometries of real patients. Computed Tomography (CT scan) is an image generation technology that uses X-Rays beams to produce images of the cross-sectional area, perpendicular to the analysed subject. Based on CT scans Dicom files, it is possible to import the CT scan data of bones into dedicated modelling software to generate the bones and create surfaces and solid parts by using additional software. ScanIP or MIMICS are some examples of software focused on the image treatment procedures by using algorithms to construct geometries.

As mentioned before, CAD models are the first step to perform a finite element analysis. In the current thesis, the software to generate the bones geometries was ScanIP from Simpleware. Autodesk Inventor Fusion 2012 and Solidworks 2012 from Dassault Systems were used to produce the models of the Ilizarov fixator parts and the assemblies. A main difficulty, in terms of modelling, is to generate the models as close as possible to the real bone. Fortunately, due to the availability on the market of novel software, it is possible to produce accurate models of real bones, based on CT scans or MRIs. Nevertheless, geometries of bones tend to be more complex than those based on
symmetrical volumes (bones modelled as cylinders). Also, meshing techniques for the FE Analysis are more complex, and the processing time is usually higher. The CAD modelling has a significant role to perform an adequate numerical analysis. Errors in this stage can produce inaccurate results and complications in the pre-processing phase, for example, difficulties to achieve a proper mesh. That is why the present Chapter stresses the importance and the relation of the CAD models with the Finite element analyses.

For the objectives of this Chapter, the general description of the procedures to create the CAD models and the FE analyses of bones and the Ilizarov frame, can be summarised in the following steps:

- CT scan data acquisition. The geometries are taken from CT scans as a series of raw images taken from different angles to produce slices of the bone tissues.
- 3D bones geometries creation. Importing the 2D images to ScanIP Software enables to generate the 3D geometries of the bones from 2D images in grey scales.
- The design of the frame geometries using CAD software such as Inventor, SolidWorks, Catia, and other.
- Verifying for errors and discontinuities in the geometries. PowerSHAPE enables verifying the geometry for errors as well as converting the surfaces defining the bones geometries into solid as well as changing geometry files to the required formats.
- Assembling the bones and the Ilizarov components. This procedure is carried out by importing the models into the assembly module of CAD software.
- Pre-processing. Applications of mechanical properties, boundary conditions, loads, displacements, mesh, and so on.
- Numerical Analysis. This is carried out in finite element software such as Abaqus.
Figure 4.1 summarises the procedures for the development of CAD models of bones and the Ilizarov frame components creation to perform the finite element analysis. Regarding the modelling of bones, the first step consists of the acquisition of CT scans or MRIs. For the purposes of this thesis, the models were created from CT scans. Once the CT scans have been taken from a real patient, the Dicom (Digital Imaging and Communication in Medicine) files are saved into *.raw or *.img extensions, taken from different scan sessions. Dicom files consist of a standardised communication protocol to store and transmit data from the Scan sessions. Compared to other files format, Dicom stores additional information such as patient’s ID (e.g. name and age) and a patient’s data cannot be separated from the CT scan related data. Once CT scans have been acquired, the procedure consists of choosing the folder that contains the data to be processed to create the 3D model. The criterion that is used to select the folder is the folder with the highest number of images with better contrast. This will provide a)
smaller spaces between scan slices, b) superior image clarity resulting in reducing the modelling processing time. Subsequently, the files are converted into *.iges files and pre-processed to identify errors in the geometries and convert it to solid models. This process is carried out in complementary software such as PowerSHAPE from Delcam. On the other hand, the first step, to model the Ilizarov components, is to obtain their dimensions and shapes. Then, in this particular thesis, to generate the Ilizarov components, CAD modelling software is used. Subsequently, the files are saved as conventional files with file extensions such as *.iges, *.sat or *.x_t. Just as in the modelling of bones, errors in the geometries can be verified using PowerSHAPE. Finally, the assembly is made using any CAD software. Hence, in the case that the model includes bones and the fixator components, both geometries are imported into the Assembly module of the CAD software. The assembly is saved into compatible analysis software formats such as *.sat, *.iges or *.x_t. The pre-processing and finite element analysis is performed in Abaqus or other available analysis software. Also, some changes in the geometry can be carried out in Abaqus or pre-processing software in order to achieve a better mesh. The purpose of the descriptions in the following sections is to provide the detailed procedures to generate the CAD models used for the numerical analyses.

4.3 Operating principles of Computed Tomography (CT scans)

The roots of the word tomography come from the Greek words *tomos* (slice or section) and *grapho* (to write). For this reason, CT scans are described as cut slices of the cross-sectioned area to be scanned. The CT scanners work under mathematical algorithms to reconstruct the images of the scanned bodies. Various procedures exist to generate the CT scan images such as the Linogram method, series expansions, algebraic reconstruction techniques (ART), expectation maximisation (EM), and others (Herman & Kuba, 1999).
Processing algorithms or double scan sources are some of the variation that improves the accuracy. Another method in modern CT scan devices uses the Fourier reconstruction whose principle is based on the results from the inverse Fourier transform. However, Pointer, (2008) suggest that the most common techniques for CT scan reconstruction are based on the application of the filtered backprojection algorithm (FBP).

In general terms, the CT scan images are constructed from multiple projections taken from different angles. Every projection contributes to the total number of voxels, which are the equivalent of pixels for 3D bodies, to create the 3D image from the CT scans. The higher is the number of projections; the better are the images. The reason is that a greater number of projections represents a greater number of voxels to generate the picture. However, there are fast imaging CT scanners that can produce good quality pictures with few projections.

Figure 4.2 shows the emission source of the X-Ray CT scanner. The source rotates around the scanned object; usually at intervals of 0.3 to 1 degree though it can be bigger depending on the particular scan device. The rotation of the source forms linear patterns where, the absorption coefficients of the series of projections are introduced into the Filtered Backprojection Algorithm (FBP) to reconstruct the image.
In order to explain the operating principles of CT scanner devices deeply, it is essential to consider firstly that CT scanners work based on X-Rays. From this starting point, the CT scanner produces images using the same principle of conventional X-Rays with the difference being that it creates the images from a series of many projections. Then, the generated images with X-Ray technology result from the attenuation levels produced by the absorption of the emitted beams by the scanned body. Consequently, bodies with a higher density and a higher number of electrons produce higher attenuation values. For this reason, bones rank higher in attenuation levels compared to soft tissues. This is because; bones contain 20 electrons of calcium, 19 of potassium, 15 of phosphorus and 12 of magnesium, compared to 6 electrons of carbon, 7 of nitrogen and 8 of oxygen in soft tissues (Epstein, 2008).

In biological materials, the attenuation coefficient determines how easy or difficult it is to penetrate a body. Hounsfield attenuation units are normalised to represent the linear attenuations coefficients in body tissues. Hounsfield units (HU) represent the attenuation coefficients of the absorbed beam energy of the CT scan sources as a function of the density of the biological materials (soft tissues and bones). As a result, every voxel in the reconstructed image is allocated a (HU) value (Brown et al., 2008). Hence, this represents the first step to create the CT scan 2D image. This coefficient is normalised in terms of the values for water as a reference where, the Hounsfield coefficient for distilled water under standard conditions of pressure and temperature is zero. Brown et al. (2008) summarise the (HU) as follows:

\[
HU = 1000 \left[ \frac{\mu(E_{CT})}{\mu_w(E_{CT})} \right] \left( \frac{\mu_w(E_{CT})}{\mu(E_{CT})} \right)
\]

(4.1)

Where, \(\mu_w\) is the linear attenuation coefficient for water with respect to \(E\), \(\mu\) is the coefficient for a particular analysed material in \(cm^{-1}\). In the case of biological tissues, bones, and soft tissues, \(E_{CT}\) is the energy emitted by the CT scanner source. Due to the attenuation coefficient of the air is approximately zero. Then, an increment of one Hounsfield unit represents 0.1% of attenuation. Hence, this coefficient changes as a
function of the material. The integer constant $K=1000$ is standardized with that value though some cases can have a value of 1024 (Goldman, 2007).

Linear attenuation coefficients for bone is +1000 while; soft tissues vary from +10 to +50 Hounsfield units (HU). The scale goes from -1000 to +1000 where values higher than 10HU represent existing solids (Rao et al., 2007). Bones, which are the tissues modelled in the current thesis have a coefficient of +1000 HU. However, values can vary as a function of the type of bone (e.g. Cortical or trabecular). In addition, the HU for bones can change depending on nutrition and age. Then, illnesses such as osteoporosis can be detected based on CT scans.

Attenuation by millimetre of the X-Ray beam can be also expressed in terms of the Beer-Lambert law as shown by Feeman (2010):

$$\frac{dl}{dx} = -A(x) \cdot I(x)$$ \hspace{1cm} (4.2)

Where $A(x)$ represent the attenuation coefficient and $I$ the intensity of the X-Ray beam. The X-Ray beam starts in the $X_0$ position coming out from the CT scan source. The initial intensity is expressed as $I_0 = I(X_0)$ and the intensity at the exit point after it passes through the scanned body is the final intensity $I_i = I(X_i)$. Then, from equation (4.2) as Feeman (2010), it results

$$\int_{X_0}^{X_i} A(x) dx = \ln \left( \frac{I_i}{I_0} \right)$$ \hspace{1cm} (4.3)

Equation (4.6) represents the relationship between the attenuation coefficients resulting from the transmission of the $(I)$ X-Ray intensity into a body along the projection.

The first CT scan image reconstruction step is based on the sum of the attenuation coefficients $X_i$ along a straight line projection of the scanned body. As shown in Figure 4.3, $N_0$ represents the intensity of the X-Ray beam produced by the CT scan source, and $N_i$ is the intensity of the transmitted X-Ray on the sensor of the CT scan detector. Thus, $\mu_1$ to $\mu_n$ are the attenuation coefficients along the projection, and $w_i$ is the slice width.
Chapter 4 Procedures for the development of solid models of bones and the Ilizarov frame components

Figure 4.3 Hounsfield attenuation coefficients matrix (Goldman, 2007)

Thus, Goldman (2007) describes $X_i$ as the sum of the attenuation coefficient values along a projection as follows resulting as: $X_i = U_1 + U_2 + U_3 + U_4 \ldots \ldots + U_n$, thus,

$$X_i = -\ln\left(\frac{N_i}{N_o}\right)$$ (4.4)

This is exactly the same equation (4.3) by Feeman (2010) where $I_0=N_0$, $I_i=N_i$ and $A(x) = X_i$ and, $U_i=W_i\mu_i$

Where, $u_i$ represents the attenuation value for a voxel and $X_i$ is represented in terms of logarithms to estimate the attenuation relation along the projection from the X-Ray emitting source to the output. Once the attenuation coefficients are calculated, it is possible to establish a simple example of how the CT scan builds images. Goldman (2007) developed a 2x2 matrix of voxels based on the values for $N_0$, $N_i$ to explain the procedure as shown in Figure 4.4.
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Figure 4.4 CT scan reconstruction based on the Algebraic Reconstruction Technique (ART) algorithm (Goldman, 2007)

Thus, sums of intensities in the columns, rows and diagonals in Figure 4.4 are represented as: $X_1=\mu_1+\mu_3$; $X_2=\mu_2+\mu_4$; $X_3=\mu_1+\mu_2$; $X_4=\mu_3+\mu_4$; $X_5=\mu_1+\mu_4$ and $X_6=\mu_2+\mu_3$.

Figure 4.4 shows how the CT scan is constructed based on a 2x2 voxels example. Figure 4.4 A, contains the general notation to describe the X-Ray values from the source beam $N_0$, the values at the output ($N_1$ to $N_6$) and the attenuation coefficients, $\mu$ for every voxel. Figure 4.4 B shows the output values of the attenuation coefficients which are unknown before the first projection. Figure 4.4 C represents the values for the first projection at the output which are divided by the number of voxels to obtain the voxel values. In this particular case this results because the value for $w_1$ is the same in every voxel as it is a square geometry. Thus, $X_1$ and $X_2$ for the first projection have the same value of 10. Every voxel space is filled with the attenuation value of 5, which is the number of voxels in those vertical projections determined by equation (4.3). Then, the second projection generates an attenuation value at the output of $X_3=14$ and $X_4=6$. The voxel values are determined again by equation (4.3) resulting as those in Figure 4.4 D.
N_i outputs. As the expected values in Figure 4.4 D are expected to be the same as those of Figure 4.4 C, because it only changed the direction of the X-Ray beam, it is essential to apply an adjustment to determine the right values for X_3 and X_4 after the second projection. This consists of subtracting the expected outputs values of 10 of the first projection from those of the second projection, thus:

\[ X_i(\text{correction coef}) = X_i - X_i(\text{expected}) \]  \hspace{1cm} (4.5)

\[ X_3(\text{correction coef}) = X_3 - X_3(\text{expected}) \]  \hspace{1cm} (4.6)

As X_3(\text{expected}) = 10 and X_4(\text{expected}) = 10 and the values of X_3 = 14 and X_4 = 6 for the second projection are already known, this results in: X_3(\text{correction coef}) = +4 and X_4(\text{correction coef}) = -4.

As this current example arrangement is a 2x2 matrix of voxels with the same w_i values, every voxel has half of the correction coefficient (+2 and -2). This results in the attenuation coefficients of the Figure 4.4 D. This adjustment process is carried out for subsequent projections; thus, N_5 = 12 has a correction value of +2. Then, +1 is added to the voxels along N_0 to N_5 diagonal resulting in the attenuation coefficient values in Figure 4.4 E. The process is the same for the final values of Figure 4.4 F. This procedure continues as many projections are required and as a function of the number of voxels containing the image. However, this algorithm was susceptible to noise usually represented by a Poisson statistical distribution resulting in random errors and poor quality images (Goldman, 2007). For this reason, subsequent algorithms were developed. The filtered backprojection algorithms (FBP) solve some of the problems of (ART).
4.4 Outline of the procedures for Creating CAD Models of bones from CT Scans

After the CT scan data acquisition, the procedure for converting the 2D images from CT scans into 3D geometries until the pre-processing step is detailed described as follows:

CT (computerized tomography) images are obtained from a real patient and then imported to ScanIP software. These images are obtained as slices, and every slice has information in grey scales that defines the geometry. As many slices as possible are required to create a 3D real patient’s bone geometry. Figure 4.5 displays the Dicom viewer showing the folders to create the geometry containing a different number of images such as 188 slices at 1 or 2mm thickness. The format of those images is Dicom files (Digital Imaging and Communication in Medicine).

![Figure 4.5 Dicom 2D images of clubfoot in babies](image-url)
Figure 4.6 Dicom 3D view of clubfoot in babies

Figure 4.5 shows Dicom 2D images of a baby’s clubfoot where every image is a slice to create the solid geometry. On the left side of Figure 4.6, raw images from the lateral view of the foot are shown. In the centre of the Figure, there is a 3D preview of the foot.

The first step is to import the Dicom files to ScanIP software made by PowerSHAPE from Delcam. The CT scan CD with the CT scan data usually has folders with the various Scan sessions. Some folders contain more images of the same geometry resulting in more information and clearer models.

When the files have been imported, a software window displays images in three planes, sagittal, coronary and axial, as shown in Figure 4.7. It enables to work from different perspectives. At the beginning, the software displays grey scale images. After importing the images in grey scales, it is necessary to apply a mask of any colour. The mask will cover the whiter dots of the images because they represent the bones.

Usually, axial plane provides a clearer perspective and so this plane is adequate to start working by filling the white dots to build the bone geometry. Before starting to work on
the geometry, it is possible to use different filters in order to reduce processing time when creating the geometry. Also, the use of filters enables the user to achieve more accurate geometries.

Figure 4.7 ScanIP perspectives of the CT scans in, the sagittal, coronary, axial planes and the preview of the solid model

Figure 4.7 shows a ScanIP slice during the bone construction. The creation of the solid requires the inner empty spaces to be filled to complete the solid model. This process must be repeated slice by slice. The changes in any of the perspectives will be automatically updated in the views of the remaining planes.
It is important to fill the gaps carefully. Clear images illustrate dense surfaces that usually generate the bones’ geometries. However, in some cases, other tissues such as cartilages can be displayed so clear that they give the appearance of bones. In order to create an accurate geometry, it is necessary to have a profound knowledge of the anatomy of the limb to be modelled.

The procedure must be repeated for every slice. Occasionally, the geometries of the bones are closer to each other. Then, after applying a filter, it can result that the gaps between bones are filled. If that situation occurs, it is necessary to create the spaces between bones by erasing the colours to separate the geometries.

Figure 4.8 is the representation of the bones geometries before applying a filter to reduce noise. Filters are algorithms that the program already contains and are usually applied when the whole geometry has been constructed. They will provide softer surfaces making possible to generate a better mesh in the Finite Element Software. The application of filters depends on the geometry. Binarization filter usually softens the surface before applying other filters. Finally, the geometries are saved in a *.iges file format, and the number of faces by geometry can be determined in this section. A higher number of faces to construct the geometry results in greater complexity of the model. Also, the file size depends on the number of faces per geometry. Figure 4.9 shows the bones geometries after applying different filters.
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The next step is to verify that there are any undesirable dots within the working space and that the geometry is continuous. Otherwise, when analysing the FE software will display an error message or meshing will be complex.

Once the geometry is ready, it has to be exported to PowerSHAPE from Delcam in order to create a compatible file with Abaqus. Usually, the extension file is *.iges which is common in design software. This extension is a surfaces format. PowerSHAPE enables the user to verify for errors in the geometry and to generate a solid from surfaces. In addition, PowerSHAPE can verify for open edges in the geometry. It is important to highlight that ScanIP imports the geometries in triangular faces. Alternative software such as 3D Max or Rhino if available are useful to reshape the geometry and achieve a better mesh. Also, pre-processing software such as Ansa, Hypermesh or Patran, have a variety of tools to improve the mesh in asymmetric geometries such as bones. For the purpose of this thesis, due to the software availability, the geometries were checked for errors in PowerSHAPE and the surfaces of the bones

Figure 4.8 Clubfoot geometries in babies before applying a filter
were improved by reshaping them using the Abaqus (version 6.10 to 6.13) tools of mesh and part sections.

Figure 4.9 shows the final geometry of a clubfoot after working on the images and applying different filters. The geometries of the bones are clean and smooth. The Talus of this model was used for the analyses of Chapter 5. The next step after verifying for errors in the geometry is to convert the surface files into solids in order to prepare them to be imported to Abaqus. As shown in Figure 4.10, it is possible to convert surfaces to solids and to save the file to Abaqus with the format *.x_t from Parasolids to perform the Finite Element Analysis. Also, the files can be imported as *.sat files.
Finally, Figure 4.11 shows the geometries imported from PowerSHAPE to Abaqus and converted into a solid model. The coordinates and dimensions of the solids are respected during the process. This is a crucial consideration when the pieces are needed to be assembled in the source position. It is important to highlight that the triangles that form the geometry can result in meshing difficulties in Abaqus. Then it is required to reshape the solid surfaces using the tools of the mesh and part module of Abaqus. Section 5.2.2 provides an example of this procedure.
4.5 Outline of the procedures for creating the CAD model of the Ilizarov fixator

As explained before, while bones require dedicated image processing software to produce the CAD model of bones, the Ilizarov fixator components are designed by using conventional CAD software such as the one used in industry. The frame components are symmetric, made of continuous, linear and homogeneous materials (stainless steel and some connectors of titanium). Their cross-sectional area is the same along the parts, and so the software used to create the drawings and the 3D solids of the components was Solidworks 2012 and Autodesk inventor Fusion 2012. Both programs have file compatibility by using the same file extension and can produce very similar results. Also, some modifications to the 3D solid models, such as cuts and 3D surfaces reshaping were made in Abaqus 6.10. Different rings, rods and wires of different sizes were designed according to the particular objectives of subsections of this thesis. While
the current thesis contains different analysis with different models, everyone is explained in the corresponding Chapter. Thus, this Chapter section is focused on a general description of the CAD procedures to create the Ilizarov frame.

The measurements of the Ilizarov frame components were taken with a digital calliper from real components. In addition, measurements taken from the manufacturer parts (Smith & Nephew) were considered. While some of the components were designed to be as similar as possible to the real components, other components were designed to satisfy certain objectives. That is the case of the Ilizarov rings that were designed without holes for some specific analyses.

An important consideration in a CAD model is setting up a consistent and reliable system of units between the model and the related analysis parameters such as loads, material properties and displacements. This is important because Abaqus is non-dimensional software in terms of analysis but, respects the measurements of the imported files from the CAD software. In order to have consistency between the CAD models and the parameters for the FE analysis, the current models and analysis were designed using the International System of Units (SI) in (mm) to create the Ilizarov components dimensions as shown in Table 4.1, from LS-DYNA support.

<table>
<thead>
<tr>
<th>Mass.</th>
<th>Length</th>
<th>Time</th>
<th>Force</th>
<th>Stress</th>
<th>Energy</th>
<th>Density</th>
<th>Young's</th>
<th>Gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kg.</td>
<td>m.</td>
<td>s.</td>
<td>N.</td>
<td>Pa</td>
<td>J</td>
<td>7.83E+03</td>
<td>2.07E+11</td>
<td>9.806</td>
</tr>
<tr>
<td>Kg.</td>
<td>mm.</td>
<td>ms.</td>
<td>kN.</td>
<td>GPa</td>
<td>kN-mm</td>
<td>7.83E-06</td>
<td>2.07E+02</td>
<td>9.81E-03</td>
</tr>
<tr>
<td>g.</td>
<td>mm.</td>
<td>ms.</td>
<td>N.</td>
<td>MPa</td>
<td>N-mm</td>
<td>7.83E-03</td>
<td>2.07E+05</td>
<td>9.81E-03</td>
</tr>
<tr>
<td>Ton.</td>
<td>mm.</td>
<td>s.</td>
<td>N.</td>
<td>MPa</td>
<td>N-mm</td>
<td>7.83E-09</td>
<td>2.07E+05</td>
<td>9.81E+03</td>
</tr>
</tbody>
</table>

Table 4.1 Examples of consistent and reliable systems of units (Hallquist, 2007)
http://www.dynasupport.com/howtos/general/consistent-units
Most of the CAD software, display a sketch area, tools to create conventional geometries (lines, circles and squares), and tools to measure and define dimensions. Figure 4.12 represent an example of the sketch of an Ilizarov component. In this case, a ring whose dimensions are 150 mm inner diameter, 180 mm external diameter and 7 mm diameter holes. To perform a faster and accurate design, the software has a tool to create circular patterns. Then, is it enough to create a single hole and to use the corresponding tool to create the set of holes. Depending on the objectives of the researcher, and the design of the FE analysis, reductions can be made. In the case of the ring design, holes and fillets are optionally omitted to make a simpler model, just considering the mechanical effects of those simplifications. Guide lines are commonly required to perform modifications to the designs. Also, a sketch can be defined over the 3D solid faces after creating the components. This is useful to perform modifications to those components. After the part was sketched, the next procedure consisted of
extruding the drawing to a specific depth. In the case of this ring, it is 5mm. Figure 4.13 shows the 3D end view of the CAD model of the ring.

Figure 4.13 CAD model of a 150mm Ilizarov ring

Ilizarov components can be designed as detailed as possible according to the analysis criteria. The components can contain holes, fillets and threads. However, threads were excluded in all the design to make the models simpler and faster for the analysis, and to achieve a better mesh for the FE analysis. Figure 4.14 shows the design of different connectors used for the assembly of the fixator in the current thesis.

Figure 4.14 Example of the CAD models of different Ilizarov connectors
Figure 4.15 Differences in the CAD model of threaded and plain rods

Figure 4.15 shows the CAD model of a threaded rod and a plain rod. The plain rod improves the mesh and simplifies the model of the Ilizarov frame. In the case of meshing a threaded rod, the mesh seed must be small because the pitch of the thread is significantly smaller compared to the size of the component. However, plain rods are a proper choice to reduce the time of analysis and simplify the model.

Figure 4.16 Full assembly of the Ilizarov fixator
Assembly is performed in the assembly module of the software. *Constrain boundary conditions* are applied between components to restrict their movement in specific directions. The position of all components of the frame is respected by the FE software when importing the model for the analysis. Figure 4.16 is an example of the completed assembly of the Ilizarov frame which is based on Kirienko et al. (2003) and the current procedures of surgeons. The Figure shows in yellow, some of the most important connectors in the frame; the hinges enable adjustments. Wires, which are shown in red, are the elements to link bones with the frame. In Chapter 5, there is an example of the full frame assembled with the model of an adult foot and ankle bones.

### 4.6 Finite element and CAD modelling in biomechanics

Numerical analyses and experimental tests provide information to validate and modify current surgical procedures, to simulate the behaviour of prosthesis and implants in the human body and to determine the possible causes of failure in some medical treatments. However, in the case of the analysis of living tissues, sometimes experimental test are complicated to perform because of the difficulty to obtain cadaveric tissues such as bones. Then, numerical analyses are a reliable tool to provide information about the behaviour of human tissues.

A numerical analysis employing Finite Element Software is a widely employed tool to predict the behaviour of systems. Nowadays, numerical analyses are supported by robust software and machines to analyse and estimate the mechanical properties of different structures. In biomechanics, numerical modelling based on computational software is useful and has gained acceptance and applicability in science and industry. It enables simulations of various human body tissues such as bones and soft tissues as well as implants and prosthesis analyses. As a result, surgical procedures, prosthesis and novel and new techniques have been developed, modified and improved and to treat diverse pathologies.
The Finite Element Method or (FEM) consists of a numerical procedure to analyse discrete elements through approximations to a continuous system. Most systems in nature describe a non-linear behaviour so by the FEM, equations describing a system are transformed in finite quantities of relatively linear equations. The equivalence of this method is given by a series of finite elements connected by mutual points between the boundaries of a geometry known as nodes. If equilibrium conditions can be applied to any node of the designed structure, then it is possible to create a set of algebraic equations as a function of nodal displacements. Thus, differential equations are defined in a continuous medium, and it is possible to analyse non-linear problems by means of approximations. Numerical data are determined with the use of different software available on the market that applies FEM, in order to analyse the behaviour of structures and systems. Some relevant variables, to determine accurate results by means of FEM, are the type of elements and the mesh techniques. This is because the nodal values represent a matrix of unknown quantities to be solved by numerical procedures. For this reason, the complexity of the analysis can change as a function of the geometry and the distribution of those nodes. The number of nodes can be mainly determined by a) the seed mesh b) the type of elements, c) the geometric order. Then, results can vary in the first and second order approximations and depending on the element type. Additional parameters such as the right boundary conditions, the proper application of loads, appropriate units consistency and others can influence the accuracy of results.

Considering that biomechanical studies are multidisciplinary, it is crucial to have a deep and clear understanding of the functions of the analysed tissues, their behaviour in the human body, their anatomy, mechanical properties and so on. Also, it is important to understand the physical function of the limb under analysis; otherwise, it is possible to achieve wrong results. The failures in the model can result from: a) improper model reductions and wrong parameters (application of loads, boundary conditions, interactions and so on), b) unknown mechanical properties for specific pathologies due to the lack of experimental studies in the literature, c) lack of understanding of the physical function of the pathology in the body. These considerations are important to achieve a reliable biomechanical model. Otherwise, the model will be inaccurate,
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complicated or inadequate to the proposed case analysis. The difference between modelling biological or lively materials in comparison to other materials is that their mechanical properties can change depending on a significant range of variables. Sometimes, it is possible to approximate the case analysis to a linear elastic, isotropic and continuous analysis, mainly at the beginning of the study. Thus, basic geometries can be produced to simulate the pathology as a first approach. This will guide to have a better understanding of the pathology so as to avoid unrealistic boundary conditions and wrong modelling considerations. This is suggested because the human limbs contain a vast amount of soft tissues surrounding the bones, giving the limbs support and stability, as well as higher complexity in the analysis. Then, sometimes it is difficult to make assumptions for reducing the model without these previous attempts. When this first step has been achieved, it is convenient to improve the model by modifying the analysis with more complex geometries, closer to those of the real tissues. This will commonly provide more accurate results. However, in some cases, a simple analysis can produce good results. When a complex geometry is generated with the purpose of creating a more realistic approach, software such as Mimics or ScanIP can be a good alternative to generate geometries from CT scans or MRI’s from a patient with a specific pathology. Then the geometries can be imported into other software to verify the geometry and then to a Finite Element Software. To proceed with the Finite Element Analysis, it is necessary to define the type of analysis (2D or 3D). In the case of this thesis, the bones are modelled as 3D solids.

In biomechanics, modelling techniques and numerical analysis enable the researcher to modify parameters, expanding the range of possible solutions to predict the behaviour of elements and systems under critical conditions. It is important to say that the advance on modelling has been achieved due to the progressive development of computing because some analyses require powerful machines to reduce the time to generate results. Another highly relevant aspect is the availability of additional software to design complex geometries to be exported to dedicated numerical analysis software. Results of the numerical analyses of biomechanical tissues depend fundamentally on seven main aspects: a) the analysis design and CAD models, b) the right boundary conditions, loads, displacements, etc., c) the available data in the current literature on the mechanical properties of the analysed tissues, d) the degree of knowledge of the
related pathology to the numerical analysis, e) reliable reductions in the numerical model, f) the techniques applied to generate, pre-processing, e.g. mesh, g) the general limitations of the case study and the numerical techniques. On the last aspect about limitations of the numerical techniques, it is possible to identify the advantages and disadvantages of using software to perform those analyses.

On the other hand, non-symmetrical geometries are difficult to be modelled by conventional mechanical design software. This is one of the main phases performing a finite element analysis. Auxiliary software such as ScanIP, Mimics and others tools provide an excellent alternative for obtaining bone's geometries from CT scans or MRI’s. This first step, the CAD model development using additional tools, provides a better solution to achieve a model closer to the real pathology.

Because of the importance of creating the best possible geometries to be analysed, in this Chapter, modelling techniques for the generation of bone tissues are shown. In this Chapter as well as the methodology to achieve it step by step.

### 4.6.1 Advantages and disadvantages of Finite Element Method (FEM) applied to Biomechanical analyses

Advantages of using Numerical analysis software are:

- The Finite Element, as a numerical method, enables analysing irregular geometries providing flexibility to the analyses. Bones, modelled from CT scans are usually irregular geometries, difficult to be studied by direct analytical methods.
- When modelling tissues and, an experimental test is difficult to perform due to the availability of bones or soft tissues, FE models enable to perform analyses to estimate the mechanical properties of those tissues based on mechanical properties of similar tissues.
The method can consider the mechanical properties of two or more materials. Some biomechanical models require different mechanical properties due to multiple tissues.

The method provides reliable results if the variables for the analysis are properly considered. Also, the FE software enables to perform simultaneous cases considering different simplifications to the models or analysing different variables at the same time, in order to investigate the same biomechanical model under various conditions.

Some of the main disadvantages are:

- The accuracy depends on the number of elements, element type and nodes. Then, a mesh analysis as a function of the number of elements can be required to verify the model. Biomechanical models can result complex.
- It can require vast computational resources and time to be processed depending on the analysis design and the complexity of the numerical model (2D or 3D models, element types, number of elements, geometry, and so on).
- Problems requiring a high accuracy or complexity can freeze the computer in some cases.
- Depending on how complex the case analysis is, it can be necessary to use specific CAD software and additional pre-processing software to achieve better results.

4.7 Summary

The current Chapter provided the description of the procedures to pre-process CT scans images as well as the description of the procedures to create the CAD models for bones and the Ilizarov frame. There are differences between CT scans and MRI’s. The latter provides clearer grey scales images that can be useful in the generation of softer tissues such as cartilages. However, CT scans are appropriate to generate more dense
geometries such as bones. The number of slices determines the accuracy of the model but in some cases can increase the time. Tissues in ScanIP software are distinguished by the grey scales but sometimes it is difficult to distinguish among different soft tissues such as ligaments, tendons or muscles.

Depending on the availability of the software to be used to generate the bones geometries, different products provide a diversity of tools to generate differences in the expected end CAD design. Depending on the criteria for the model design such as time and accuracy, complementary software provides additional tools. For example, geometries generated in scanIP as surfaces determined by triangles can be reshaped using additional software such as Rhinoceros 3D or 3D Max. Depending on the ScanIP version, it is possible to create Non-surfaces based on uniform rational basis spline (NURBS) instead of polygons that provide improved surfaces, these results in cleaner geometries whose shapes are easier to be meshed. In the side of CAD modelling, Autodesk Inventor, CATIA, Solidworks so on, provide different tools that can complement to each other. Some of them are more versatile in the tools to create CAD designs while others are easier to use and others employ less time to achieve the same results. On the other hand, the availability and use of pre-processing software such as Hipermesh, Patran, Ansa, and so on, can help to reduce the modelling time and increasing the accuracy. The reason for using a diversity of software is because some software is focused on the CAD design, while others in the pre-processing and others in the analysis. However, as mentioned before, it depends on the time and expected accuracy for the model. For the objectives of the present thesis, the summary of the utilised software is ScanIP to create the bones models, Autodesk Inventor Fusion 2012 and Solidworks 2012 to create the Ilizarov frame parts, PowerSHAPE from Delcam to generate solids, verify error in the CAD models and change the file format. Finally, Abaqus 6.10 from Simulia was used to perform the Numerical analyses.
CHAPTER 5

Finite Element Analysis of the effects of compressive loads on the talus of babies with clubfoot

5.1 Introduction

The talus has a significant role in the movement of the body and distribution of loads to the other bones in the foot. As described in Chapter 2 on the anatomy, talus is the bone directly in contact with the tibia and fibula and is part of the ankle joint. Also, it has interaction with the calcaneus which is another big bone in the foot. As the foot provides stability to the upper limbs, any alteration in the foot and ankle results in pathologies in the foot and upper limbs. Common pathologies in adults lead to total ankle replacements where implants involve perforations and cuttings in the talus; the main cause for Total Ankle Replacement is cartilage attrition which produces pain. Other pathologies involving the talus are arthritis and osteoporosis. On the other hand, in the case of clubfoot, the talus has been reported in the literature, to be affected by deformations produced by corrective clubfoot procedures such as Ponseti (Brand et al., 2006), that is one of the most popular conventional corrective procedures for clubfoot and it has represented to be a very good alternative to treat clubfoot in new-born babies (Richards et al., 2008; Sud et al., 2008). Then, understanding the behaviour of this tissue provides information to improve the corrective procedures. Another relevant aspect is that most of the researches applying modelling techniques have focused on the analysis of adult tissues whose mechanical properties are completely different from those of new-born babies and kids. The study of the tissues in babies is relevant because it is well known that soft tissues are softer in babies (Fripp & Singer, 1953) and corrections provided after six months can result in future relapse cases. Also, there are limitations to performing analyses which is due mainly to the lack of material property database and
there are limited mechanical tests to investigate the mechanical properties of babies bones (Mahmoodian et al., 2009). This lack of test data is due to the difficulties in obtaining cadaveric bones. However, the numerical analyses enable to estimate the mechanical behaviour of tissues under different conditions. (Dobbs et al., 2000) mention that Rogers and Dickson developed the subcutaneous tenotomy, which is a simpler and easier procedure, with minor complications compared to the Achilles tenotomy. The method was developed in 1834 but did not become widely applied until 1866. They studied the effects of this procedure with several new-born babies; they noticed that the only bone that presented a serious deformity in clubfoot is the talus.

Understanding the behaviour of the talus in babies subjected to different compression conditions can provide guidance to the surgeons to determine novel treatments for foot and ankle pathologies and modifying the current procedures by considering the consequences of applying excessive corrective loads and displacements. In the case of the Ilizarov frame, there is no specific guidance to apply the procedures in babies and neither is there any guidance to state that it is safe. To address the issue of safety, it is necessary to start firstly by investigating the mechanical behaviour of these tissues to understand how they behave under different loading conditions. In the case of the corrective procedure for clubfoot by different techniques, this will enable the determination of the right surgical path without producing excessive stress that can result in (permanent) plastic deformations in the tissues. In the case of the Ilizarov frame as a corrective procedure for clubfoot, this study is the first study to determine safe conditions for the application of the Ilizarov frame to correct clubfoot in babies. In this pathology, compressive forces between tissues are involved in the correction and the talus is one of the most affected bones because is placed in the ankle joint. For these reasons, the present Chapter describes the FE analysis of the talus bone of babies under different axial compression levels, starting from a confined analysis of the talus. A mesh sensitivity analyses was performed by comparing the results from three different Abaqus element types to establish the stable zone of the model. Also, different ANN algorithms were trained with the stress values from C3D10I for 16 random nodes. The algorithms with the best fitting curve were identified. Section 5.4 explains the purpose of these analyses deeply. Also, the basic principles of neural networks are explained in section 5.4.2.
5.2 FE model of the compression of the talus by a Confined Analysis

The 3D confined analysis of the talus of babies was performed and verified by the experimental results of the compression of the talus, carried out by Mahmoodian et al. (2009), as this is the only study in the literature to determine the modulus of elasticity and Poisson’s ratio in the talus for new-born babies. They, performed experiments on confined samples of the talus of 7 and 8 months foetus by obtaining cylindrical samples of 3.29± 0.14mm diameter and 1.61± 0.37mm thickness. Mahmoodian et al. (2009) determined the mechanical properties of the talus as $E_{CT}=0.15 \pm 0.07$ MPa and $\gamma_{CT}=0.4 \pm 0.06$. Therefore, the CAD modelling of the sample was performed in Abaqus 6.13, as well as the assembly and the FE analysis. The talus was modelled as a cylinder of 3.29 mm diameter and 1.61 mm thickness, with a modulus of elasticity for a confined case of $E_{CT}=0.15$MPa and Poisson’s ratio of $\gamma_{CT}=0.4$, to match the mechanical properties and dimensions described by Mahmoodian et al. (2009). The total volume of the cylinder was calculated as 13.69 mm$^3$ and the top and bottom contact surface area was 8.54 mm$^2$ for each surface. The geometry was partitioned in order to achieve a better mesh as shown in Figure 5.1.

![Figure 5.1 Geometry partitions for mesh improvement](image-url)
Subsequently, the geometry was assembled with two analytical rigid plates, one at the top and one at the bottom. One of the plates was constrained with encastre boundary condition in order to limit its movement in all directions. The other plate was used to apply the displacement to the cylinder. In order to confine the cylinder, its movements in the X and Y directions were constrained as shown in Figure 5.2. This way, the displacement of the cylinder during the simulations was limited only to the Z axis. Figure 5.2 shows the assembly of the two plates and cylinder as well as the boundary conditions applied to the cylinder, modelled as the confined talus. The Figure shows the upper plate with an arrow in the corner indicating the direction of the displacement. The coordinate system at the top and centre of the cylinder shows the Z axis, the direction in which the displacements were applied. Also, the cylinder shows boundary conditions to restrict the cylinder movement in the X and Y directions to simulate a confined cylinder.

The cylinder was meshed using the Abaqus element types: C3D6 for the central part of the cylinder and C3D8R for the rest of the cylinder in order to have a balance between time and accuracy in the model. The analysis was performed in Abaqus using (NLGEOM) for non-linear geometries, to consider the effects of large displacements in
the simulation. A mesh analysis was performed as shown in Figure 5.3. The stable zone of the mesh analysis shows convergence above 1000 elements.

![Figure 5.3 Mesh analysis of the confined talus](image)

The sample was analysed by applying a compression displacement starting at 0.01 mm until 0.05 mm in intervals of 0.01 mm to obtain the principal stresses in the sample at different compression levels. Table 5.1 presents the stress and strain values obtained from the Finite Element Analysis of the confined talus. The values in Table 5.1 show a maximum displacement of 0.5 mm. The experimental work by Mahmoodian et al. (2009), provides data until 0.2 strain. Therefore, the predicted stress-strain values cover compressions greater than 0.3 mm.

<table>
<thead>
<tr>
<th>Compression (mm)</th>
<th>Max Principal Stress (MPa)</th>
<th>Strain</th>
</tr>
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<tbody>
<tr>
<td>0.1</td>
<td>0.0120</td>
<td>0.06221</td>
</tr>
<tr>
<td>0.2</td>
<td>0.0306</td>
<td>0.12422</td>
</tr>
<tr>
<td>0.3</td>
<td>0.0403</td>
<td>0.18633</td>
</tr>
<tr>
<td>0.4</td>
<td>0.0555</td>
<td>0.24844</td>
</tr>
<tr>
<td>0.5</td>
<td>0.0717</td>
<td>0.31055</td>
</tr>
</tbody>
</table>

Results from the confined experimental tests from the literature and the FE analyses reported in this thesis were compared and shown in Figure 5.4. The Figure shows in red
the principal stress values obtained experimentally by Mahmoodian et al. (2009) and in blue colour the FE results obtained in this thesis. The results from the FE analyses and the experimental compression test describe a similar behaviour and values. The minimum differences can be attributed to the plus-minus range establish by the experimental work where Mahmoodian et al. (2009) show a range of the modulus of elasticity and the Poisson’s ratio: $E_{CT} = 0.15 \pm 0.07$ MPa and $\nu_{CT} = 0.4 \pm 0.06$. Also, it can be attributed to slight measurement errors as the experimental data were obtained by manually interpolating the graphical data in Figure 5.4 of the publication by Mahmoodian et al. (2009).

\[ \text{Figure 5.4 Stress-strain comparison between experimental and FE results} \]

On the other hand, Figure 5.5 shows the FE results with a linear fit. At 0.2 strain, the stress is approximately 0.044 MPa. From the experimental test results, at 0.2 strain, the stress is 0.0446 MPa, approximately. Therefore, the stress values predicted and measured at 0.2 strain are very close, the deviation between them being about 4%.
Figure 5.5 Stress-strain FE results with linear adjustment

Figure 5.5 shows the stress distributions in the confined sample at the maximum displacement level of 0.5 mm. The Figure shows that the maximum stress is, also shown in Table 5.1. The Z axis in Figure 5.6 represents the direction of application of the load and the sign in the stress Table indicates compression in the FE simulation.

![Stress-strain FE results with linear adjustment](image)

**Figure 5.6 Principal stresses in the confined talus sample at 0.5 mm displacement**

The modulus of elasticity was derived from the values of the FE analysis at 0.3mm displacement to compare with the results from Mahmoodian et al. (2009) which was...
achieved at strains of up to 0.2. The obtained value from the FE was 0.21 MPa, which is within the reported range of $E_{CT}=0.15 \pm 0.07$.

By considering the 0.2\% offset from the stress-strain curve in the experimental results, the proof stress is estimated to be 0.02 MPa. This value is important in order to establish a safe compressive zone of the talus. Thus, this value may be considered as a limit for compression when analysing different clubfoot corrective procedures in future studies.

### 5.3 General procedures for modelling the talus of babies from CT scans

As described in Chapter 4, analysis of biomechanical models consists on a series of steps involving the CAD model of the biological tissues. The material properties are based on a mechanical test from the literature where the modulus of elasticity and Poisson’s ratio were determined (Mahmoodian et al., 2009). However, there is no report of the yield strength for the babies’ talus. The procedures for the development of the model are based on the description provided in Chapter 4. The explanation for the construction of the specific model of the talus is provided in the following sections. ScanIP 3.2 from Simpleware, PoweSHAPE 2010 from Delcam, Autodesk Inventor 2012, Solidworks 2010 and Abaqus 6.10 to 6.13 from Simulia are the software used to generate the CAD model and results of the Finite Element Analysis. The analyses were executed in an Intel core quad computer running at 3.0GHZ and 8 GB of RAM based on Windows XP Operative System. The CAD model of the talus was created based on CT scans of the foot and ankle of a baby. The scans were provided by a surgeon working in collaboration with the NHS at the Children’s Hospital, at Manchester Royal Infirmary.

The model was performed a mesh analysis varying the number of elements against the predicted stress values and comparing the results from three Abaqus element types. Compressive displacement of 2 mm was applied to the model in all the analyses of the mesh sensitivity study.
5.3.1 Development of the 3D model of talus from CT scans

The 3D model of the talus was constructed with 188 CT scans, taken at 1mm intervals from the foot and ankle of a new-born baby with clubfoot. The CT scans were processed in ScanIP where, based on slices, the full model of the foot was produced. The talus was imported as a surface model with *.iges extension file. The surfaces were constructed by polygons where, a large number of polygons (triangles that define the bone surfaces) generate a more accurate geometry but a more complex model. The procedures to generate the geometries were based on the description provided in Chapter 4. The voxels with higher brightness are commonly associated with denser tissues such as bones. For the modelling of bones, CT scans provide a good alternative for modelling. This is because they create clear images of the denser tissues such as bones but reduced clarity of the soft tissues.

Figure 5.7 Foot of a newborn baby from upper view

Figure 5.7 provides a clear example of the CT scan slice taken from the Centricity Dicom viewer 3.0 from LG. The Figure shows two round geometries in whiter grey scales that represent bones of the foot while the remaining areas are soft tissues (flesh, veins, ligaments, tendons, fat, muscles, and cartilages). The black colour in the image is the background. The biggest round geometry in the picture is the tibia while the fibula is the smallest one. Two important aspects are relevant in the image from the modelling perspective. Firstly, the soft tissues are difficult to model using CT scans because of the low contrast of the grey scales. However, CT scans provide more accuracy in the
modelling of denser tissues such as bones. The second aspect is clearly visible in the geometry of the tibia; the differences in the density of the cortical and trabecular bone. The former is the denser of the two bone tissues and it commonly forms the external contour of the bone. In the inside, the trabecular bone displays spongy tissues. In the case on the talus in babies, the bone has a huge percentage of cartilage. For this reason, the mechanical properties in babies are different compared to the bones in adults. The talus in the current analysis was modelled as a full solid body.

Figure 5.8 CT scan of the lateral view of a newborn baby clubfoot

Figure 5.8 shows the lateral view of the foot from a CT scan. The talus is identified in the image by the geometry inside the red circle. In addition, other bones such the tibia, fibula, calcaneus and some phalanges are shown in the Figure. Filters can be applied to soften the images, reduce noise, or increase the contrast of the images. There is not a specific rule and specific filter for all the projects. It depends on the obtained results during the processing of the images. However, some filters such as binarization are better applied in the final steps. In the current model of the talus, Figure 5.9 provides an example of the application of a mask to improve the visualisation of the contours of the bones. The gaps to close those contours are the voxels to be filled to generate the bones geometries. The process was repeated voxel by voxel and slice by slice until a preview of the bone was obtained as shown in the 3D perspective of the model in Figure 5.9. In the current model, morphological filters were applied after the masks to increase the sharpness of the CT scan slices.
Before completing the 3D model of the talus, the file was saved in ScanIP as a *.sip extension file, native from the software. Once the model was completed and following the procedures described in Chapter 4, the single talus was imported into an *.iges file which contains surfaces.

Figure 5.10 3D model of the Talus from a CT scan of a newborn baby
Figure 5.10 shows the imported surfaces of the talus of a baby, created by small polygons of different sizes. After converting the surfaces into solids in PowerSHAPE, it is still necessary to reshape the surfaces of the model in order to increase the mesh quality. This process was carried out in Abaqus and is explained in the following section.

### 5.3.2 Finite element analysis procedures

An unconfined analysis was performed based on the obtained geometries from CT scans. The 3D model of the talus from ScanIP was imported to PowerSHAPE from Delcam to verify errors in the geometry and to convert the surfaces of the talus into a solid model. Then, the model was saved into a *.sat extension file. Two round plates of 150 mm diameter and 20 mm depth were created in Autodesk Inventor 2012 to be used as platters to perform the cuts in the bone. Subsequently, the talus was imported to the “assembly” module of Inventor and assembled with the two round plates.
Afterwards, the assembly was saved as a *.sat file and imported to Abaqus to perform a cut in the top and bottom of the talus as shown in Figure 5.11. The cut was performed in the “assembly” module of Abaqus, in the menu instance and using the “merge/cut” tool. The talus was picked up as the instance to be cut while the round plates were the parts to perform the cuts. The bone, resulting from the cuttings of the plates, was the retained geometry for the assembly of the compression test. The purpose of this cutting was to provide a uniform surface for the compressive load application. Figure 5.12 shows the cuts performed to the bone where 5.12 a) is the view of the top of the bone, 5.12 d) is the lateral view, 5.12 c) is the bottom view and 5.12.d) is enables to show the top cut and part of the front and lateral sides of the bone. The initial volumes of the talus before performing the cuts were calculated in Abaqus as \( V_0 = 3771.13 \text{ mm}^3 \) and \( V_f = 3492.48 \text{ mm}^3 \) where, \( V_0 \) is the initial volume before performing the cut and \( V_f \) the final volume after the cut. The top surface area as a result of the cuts was \( A_{\text{Top}} = 65.01 \text{ mm}^2 \) and the bottom area \( A_{\text{Bottom}} = 242.78 \text{ mm}^2 \).

The geometry of the talus was created by small polygons, mainly triangles. Then, small edges resulted from the cuts around the cutting areas. Abaqus creates the mesh based on the geometrical key points of the line faces of the model. Then, the cuts produced small triangles with angles smaller than 35\(^0\). This represents distorted elements after meshing the model and means general difficulties to generate a good mesh. Also, it increases the error in the results due to stress concentrations around small triangles and non-homogenous size of the mesh elements. For this reason, the surfaces of the model were reshaped by using the tool “combine faces” in the Abaqus module “mesh”. This generated a virtual topology with bigger faces and commonly results in an improved mesh. Also, it reduces the distorted elements in the model. Figure 5.12 (a), (b), (c) and (d) show small faces on the edge of the cutting.
There are different options to reshape the geometry in Abaqus. One option consists of creating many partitions to the model and then, applying the Abaqus tools to create a virtual topology to join the small triangles into the partition areas. This is a proper choice to improve the mesh in big models. However it increases the time to reshape the surfaces. The second option is just creating the virtual topology by adding adjacent entities to create bigger faces. This is a faster procedure and commonly results in an improved mesh. This is the option applied to improve the mesh of the current model where Figure 5.13 shows the differences in the edges in the adjacent areas of the cutting edge, compared to those edges before reshaping the surfaces.
Figure 5.13 Reshaped surfaces of the model of the Talus.

Figure 5.13 is the final geometry of the talus after creating the top and bottom cuts and reshaping the surfaces of the geometry to create bigger faces. This is the geometry to be used in the final assembly with the plates for the compression test.

Figure 5.14 Mesh comparisons between native ScanIP polygons and reshaped geometry surfaces. a) ScanIP geometry, b) reshaped geometry in Abaqus

Figure 5.14 shows the mesh differences between a) the non-reshaped model and b) the reshaped model in Abaqus. The elements in yellow represent distorted elements which commonly have angles inferior to $35^0$ and higher than $120^0$. The distorted elements result in errors in the computation of the stresses. The higher the number of distorted elements is, the higher the degree of error. Figure 5.14 B) is a meshed part free of
distorted elements. Also, it reduces the computing time and increases the accuracy of the model.

![Differences in the mesh of the talus as a function of the number of elements](image)

*Figure 5.15 Differences in the mesh of the talus as a function of the number of elements*

Figure 5.15 shows the differences among meshes. While coarse mesh results in a faster analysis, fine and very fine meshes result in smaller variations in the results according to the performed mesh analysis of the current Chapter as described in section 5.3.

In order to optimise the computer resources, two square and solid analytical rigid plates of 150x150 mm were created in the “part” module of Abaqus to apply the compression to the model of the talus. Then, they were assembled by using as a reference points the nodes of the edges of the plates that were used for the cuts. Thus, the analytical plates were placed in the same position as the round plates in order to keep the exact same position. Analytical plates were used because they do not need to be meshed. This results in less number of the total elements in the model and reduces the analysis time.
Figure 5.1 shows the assembly of two analytical rigid plates on the top and bottom of the talus solid model. Figure 5.1 a) show the assembly before reshaping the talus and Figure 5.1 b) shows the reshaped geometry. Reference points were placed in the corner of the analytical plate to collect the stress and displacement data. The mechanical properties of the talus were determined based on the only mechanical test in the literature on the study of the talus in a cadaveric eight months foetal talus (Mahmoodian et al., 2009). The modulus of elasticity was $E_{\text{Talus}}=0.06$ MPa and the Poison ratio as $\nu_{\text{Talus}}=0.4$. Contact properties between the plates and bone surfaces were assumed to be a surface to surface contact and tangential behaviour with a friction coefficient of 0.1 as the literature suggest values from 0.005 to 0.13 between cartilage and metal (Merkher et al., 2006). Normal behaviour was established as hard contact, which is the default property by Abaqus. Then compressive displacements from 1mm to 5 mm were tested by applying boundary conditions of “displacement/rotation” in a reference point placed in the corner of the upper plate and encastre Boundary Conditions (BC) in the reference point of the bottom plate. The analysis step was configured for nonlinear geometries (NLGEOM) to consider the effects of large displacements.
5.4 Mesh analysis for the talus from CT scans

One of the main problems in numerical analyses is to ensure the reliability of the results. Biomechanical models are usually complex compared to conventional models. In order to analyse the reliability of the results in a model, a mesh sensitivity analysis is a conventional and commonly used method. A mesh sensitivity study is a procedure to establish the optimal mesh density in order to have a balance between accuracy in the results and computing time. One of the most common procedures to perform a mesh sensitivity study, applied to different models in the literature, consists of analysing the same model (same assembly, boundary conditions, interactions, loads, and so on) but, varying the mesh size. Therefore, by modifying the mesh size, the mesh density of the model changes as well as the number of elements, resulting in coarse to fine meshes. Subsequently, the number of elements of every mesh variation is plotted against their corresponding stresses value at a critical point, such as the maximum stress of the model or the maximum stress in a specific critical location of the model. The relationship between the stresses as a function of the mesh density results in the establishment of the stable zone of a model where, results in the stable zone present minimum variations as a function of mesh size. Therefore, it is possible to perform analyses to the model using the lowest number of elements to reduce the computing time and obtaining reliable results.

However, symmetric and non-complex geometries with no singularities, produced by conventional CAD software, provide more predictable stress distributions along the model than biomechanical models of bones that are constructed based on CT scans or MRI’s. This is because biomechanical models of bones are not symmetrical. They have different cross-section areas along every mm of the model and contain a big number of faces. Some models result to be complex and with concentration stress nodes due to asymmetries of the geometry. Therefore, performing a mesh analysis to identify the stable mesh zone based on the stress values from a single node, may not be as reliable as analysing the mesh density in more than one node, or all the nodes rather than a single node.
On the other hand, analysing the stress variations as a function of the mesh density for all nodes, can result in a vast amount of time but may ensure the reliability of the model. Artificial Neural Networks have proofed to be a good alternative to analyse a vast amount of data in acceptable computing time to predict the behaviour of systems and models. This Chapter used ANN in order to analyse the stress behaviour as a function of the mesh density in 16 random nodes rather than a single node as in conventional mesh procedures. The target was to identify the algorithms that provided the best fit compared to the training data from the results of the FE mesh analysis. Therefore, the identification of those algorithms can be useful to be applied in subsequent studies to condensate the data from more than one node in a single stress vs mesh density relationship, based on the stresses from all nodes in the model rather than a single node.

The proposed application of this thesis is not intended to substitute the conventional mesh sensitivity study as it still requires the results from FE to train the ANN. Rather than this, it is considered to condensate the results from the stresses as a function of the mesh density for more than one node into a single curve, to improve the reliability of the mesh sensitivity study. The section dedicated to this purpose was constrained to the identification of the best training algorithms to perform this task. Therefore, few pages were dedicated to this purpose, as the thesis is centred on the analysis of the Ilizarov frame and the analysis of the talus of babies rather than ANN and/or mesh analysis procedures.

The mesh sensitivity study performed in this thesis compared the results of the maximum stresses from three different tetrahedral element types in Abaqus two of second order, C3D10I (Improved surface stress formulation) and C3D10, and one of first order, C3D4H (Hybrid formulation). Therefore, the stable zone was identified and compared among the results from three element types. The ANN were trained with five training algorithms, Scaled Conjugated Gradient, Levenberg-Marquardt, Resilient Backpropagation, Fletcher-Reeves Conjugated Gradient (C. G) and Broyden-Fletcher-Goldfarb-Shanno (B. F. G. S) Quasi-Newton. The following section presents the results of the mesh convergence study.
5.4.1 Results of the Mesh convergence study

A mesh sensitivity study was carried out in order to determine the mesh size of the area where, the number of elements does not represent significant variations in the results (stable zone). The tetrahedral mesh elements of Abaqus compared in this study were C3D10I (Improved Surface Stress Formulation), C3D10 and C3D4H (Hybrid formulation), where, the first two are second order elements while the last one is first order.

![Mesh sensitivity study for the model of the talus of a baby](image)

Figure 5.17 Mesh sensitivity study for the model of the talus of a baby

Figure 5.17 shows the results of the variation of the stress as a function of the number of tetrahedral element in the model of the talus. The compressive displacement for the mesh sensitivity study was 2mm for all the cases. As shown in Figure 5.17, the first element type that displays convergence is the C3D10I, which means that a medium size mesh provides few variations in the results starting with a relatively stable region prior to 5000 elements with a slight variation at about 7000 elements. The element types C3D10 and C3D10I show an overlapping section after the number of elements in the model is increased to 12000. The element type C3D4H does not present convergence in
the tested area. This is because linear elements converge with very fine meshes. The faster convergence of the second order elements compared to the first order elements is expected as second order elements provide intermediate nodes. This represents a higher number of nodes but increases in the computing time. The chosen element for the current analysis was C3D10I because it converges with a small number of elements and decreases the time to run the analyses. In addition, C3D10I is optimal for surface to surface contacts and commonly matches the analytical results when compared. Due to the increment in the number of nodes, it provides similar results to hexahedral elements. However, because of the asymmetry of the bone and the changes in every millimetre of the cross section area, tetrahedral elements are appropriate.

Table 5.2 Maximum Von misses stresses as function of the number of elements for 2mm compression.

<table>
<thead>
<tr>
<th>Number of Elements</th>
<th>Stress (C3D10) (KPa)</th>
<th>Stress (C3D4H) (KPa)</th>
<th>Stress (C3D10I) (KPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23860</td>
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<td>16.763</td>
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<td>17063</td>
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<td>26.933</td>
<td>18.142</td>
</tr>
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<td>2986</td>
<td>23.07</td>
<td>20.964</td>
<td>25.116</td>
</tr>
<tr>
<td>2919</td>
<td>18.480</td>
<td>24.632</td>
<td>41.586</td>
</tr>
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<td>2849</td>
<td>17.286</td>
<td>16.746</td>
<td>17.195</td>
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<tr>
<td>2812</td>
<td>17.503</td>
<td>20.732</td>
<td>26.481</td>
</tr>
<tr>
<td>2730</td>
<td>23.681</td>
<td>26.061</td>
<td>26.290</td>
</tr>
<tr>
<td>2635</td>
<td>17.150</td>
<td>21.251</td>
<td>17.228</td>
</tr>
<tr>
<td>2595</td>
<td>23.453</td>
<td>14.009</td>
<td>24.878</td>
</tr>
<tr>
<td>2592</td>
<td>17.066</td>
<td>14.299</td>
<td>26.697</td>
</tr>
</tbody>
</table>

Table 5.2 summarises the variation in the stresses as a function of the number of elements in the model of the talus. The minimum number of tested elements was 2592
elements at 5 mm mesh size while the finer mesh of 1 mm provided 23860 elements. The results from the element type that presented the best convergence curve were used to train the Artificial Neural networks for the purposes described in Section 5.4.

Complementary to this analysis, the mesh convergence was performed to analysed 16 random nodes in the edges of the top and bottom cuts of the model and produced by the resulting key points from the reshaping of the model, as shown in red colour in Figure 5.18. Every single node was identified by the same coordinate (X, Y, Z) for all the mesh densities. Considering the coordinates of the nodes provided accuracy to identify the same nodes with different mesh densities. A database from the analyses of 2mm displacement in 16 nodes was created and compared with the convergence trend curve for the maximum stress at 2mm displacement.

![Random nodes for the mesh sensitivity analysis](image)

*Figure 5.18 Random nodes for the mesh sensitivity analysis*

Figure 5.18 summarises the nodes used for the mesh sensitivity analysis by the highlighted nodes in red colour. In the left side, the bottom view describes ten nodes around the edge of the surface. This is because the surface area is bigger in this cut surfaces. In the right side, the top view shows in red colour 6 nodes around the edge of the cut and 10 nodes in the bottom. These nodes were created randomly by the reshaped faces in Abaqus. The coordinates for every single node were the same for every mesh density and identified by an ID node number.
Chapter 5 Finite element analysis of the effects of compressive loads on the talus of babies with clubfoot

Figure 5.19 Mesh convergence studies of the stress in 16 random nodes and the maximum stress at 2mm displacement

Figure 5.19 display the plots of 16 random nodes in the model. Nodes 1 to 10 correspond to the stress values in the bottom cut face of the model. Nodes 11 to 16 are the stresses in the random nodes of the top cut surface. The blue dotted curve in the Figure shows the maximum von misses stress for 2mm compression in 16 random nodes and the node with the maximum stress in the model. It was verified by this additional analysis that, convergence in the model occurs in a mesh density of more than 7000 elements and more than 10000. Element numbers between 2892 and 7000, consist of the transient zone while more than 10000 are the stable zone of the model. The random nodes mesh convergence study was made to verify the convergence zone of the full model rather than just analysing one node at the maximum stress. This provides a higher accuracy of the model. As a result of the mesh sensitivity study, the mesh zone for the current model was established to be into the stable zone where more than 10000 elements are used with an Abaqus element type C3D10I. The following Sections, Section 5.4.2 describes the basic concepts on Artificial Neural Networks while Section 5.4.3, describes the use of neural networks according to the purpose described in Section 5.4.
5.4.2 Review of the basic principles of Artificial Neural Networks

Artificial Neural Networks consist of the analogy of the way the brain works to be applied to machines. The first explanations on the functions of the brain and mind were given by Plato and Aristotle (Hilera & Martinez, 2010).

Artificial Neural Networks (ANN) are based on the function of biological neurons applied to computational models. As shown in Figure 5.15, the main parts of a biological neuron are the nucleus inside the cell body. From the body, there are ramifications whose terminals are the dendrites. Their principal function is to connect with other neurons. These connections are called synapses. Axons are covered by a liquid called myelin. Anderson (2007), states that synapses between particular neurons are stronger than others. This is the key to interpret the analogy between computational and biological models. The strength of the synapses of biological neurons represents the concept of weight in ANN. Figure 5.20 shows the general scheme of a neuron.

![Figure 5.20 Scheme of a biological neuron](image)
Izarrueta and Saavedra (2008) highlight two main aspects of the model of biological neurons applied to artificial neural networks:

The input signal and the output signal depend on the learning process that reinforce and strengthens the synapse. This represents the concept of weight in ANN.

The sum of the input signals from the synapses established between dendrites take place in the cell body.

In 1950, Rosenblatt developed a basic model of a neural network, based on the previous model of McCulloch and Pitts, described by (Hagan et al., 1996). The main contribution of Rosenblatt was introducing the training rule where the perceptrons converge to the right weight values as a result of the learning process of the Neural Networks (Hernandez-Hernandez, 2010). Propagation and transfer function are the main steps of the perceptron where results from the transfer function of the output are the back propagation of the neural network. This is the main aspect that enables learning in the ANN. Figure 5.21, is an example of the architecture of a perceptron.

![Figure 5.21 Scheme of a perceptron (Hernandez-Hernandez, 2010)](image)

On the other hand, Haykin (1999) defines an ANN as a powerful processor in parallel, able to store knowledge from experimental situations and make it available which is
similar to the processes of the brain. In 1943, McCulloch and Pitt presented a simple and one of the first models of an ANN base on logic gates. Figure 5.22 shows the scheme of the analogy of a biological neuron with an artificial neural network where, \(X_1, X_i, \text{ and } X_n\) are the inputs in the dendrites coming from the synapses.

Depending on the strength of the synapse, every input is associated with a weight value represented by \(W_{ji}, \text{ Wji, and Wjn}\). Then, In ANN, every signal from the vector \(X_i\) is multiplied by the values of the vector weights \(W_{ji}\) and this represents the value of the synaptic weights that can be positive (excitatory) or negative (inhibitory).

\[
X_i = (X1, Xi, ..., Xn) \quad (5.1)
\]

\[
W_{ji} = (Wj1, Wji, ..., Wjn) \quad (5.2)
\]

The sum of the input values is calculated in the cell body and is represented as:
\[ Y_j(\text{in}) = \sum_{i=1}^{n} W_{ji} X_i \]  

(5.3)

where \( Y_j(\text{in}) \) is the result of the sum of inputs. However, the neuron requires an activation function to be applied to the values of \( Y_j(\text{in}) \) and activation threshold value resulting in the sum of the output values of the neural network represented by \( Y_j(\text{out}) \).

\[ Y_j(\text{out}) = \gamma(\sum_{i=1}^{n} W_{ji} X_i + V) \]  

(5.4)

Activation functions or transfer functions can be linear or non-linear. Some of the most common transfer functions to activate ANN are linear transfer functions, sigmoid, sinusoid, Gaussian and unit step function.

### 5.4.3 Implementation of Artificial Neural Networks

The procedure consisted of analysing sixteen random nodes at the edge of the cuts in the upper and lower faces of the talus as shown in Figure 5.18. The database is reported in Appendix 2 of the current thesis. The plots of the values for every node are reported in the Appendix 3. This database was used to train five different ANN algorithms in Matlab 2010. Then, the algorithms that provide a better fit to the FE stress values from the nodes using the element type C3D10I as mentioned in Section 5.4 were identified. The Training algorithms used in the current Chapter are summarised in Table 5.3.

Firstly, five different algorithms were tested using as training data the values of the stress and number of elements from the FEM results of the maximum stress at 2mm displacement, using the C3D10I Abaqus element type. A 70% of the database of the neural network was used for training, 15% for validation and 15% for test. A maximum total of 200 epochs (which is the number of iterations inside the hidden layers) and architecture of 2-15-1 neurons were simulated where, 15 is the hidden layer, and 2 and 1 correspond to input and output vectors. As shown in Figure 5.23, the black line represents the results from the FEM using the C3D10I element type with the maximum
stress values at 2mm compression. The algorithms, BFGS Quasi-Newton in orange colour and Levenberg-Marquardt in green colour, overlap the results from the FEM using the C3D10I element type of Abaqus in black colour. While Levenberg-Marquardt shows convergence over 15000 elements, the Neural Network trained with BFGS Quasi-Newton shows very similar convergence compared to the results of the FEM. This may be expected as the algorithms for the solution techniques in Abaqus are based on full Newton and Quasi-Newton numerical methods. However, the analysis was extended to 16 random nodes to identify the algorithms that provide the best training for the mesh analysis using tetrahedral elements, and to ensure that those algorithms shows the best fit to the FEM curve in black.

Figure 5.23 Mesh sensitivity analysis comparisons by using Artificial Neural Networks

As mentioned before, cases were compared for sixteen random nodes by considering as the main criteria the mean square error and the algorithms that fit better the results from the FE model, used for the training, validation, and test. For the first node, the training algorithm, Levenberg-Marquardt resulted in a mean square error of 1.8942e-007, as shown in Figure 5.24, while Table 5.3 summarizes the training algorithms tested in this analysis.
Table 5.3 Training algorithms (Hernandez-Hernandez, 2010)

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Matlab Code</th>
<th>Acronym</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levenberg-Marquardt</td>
<td>trainlm</td>
<td>LM</td>
</tr>
<tr>
<td>BFGS Quasi-Newton</td>
<td>trainbfg</td>
<td>BFGS</td>
</tr>
<tr>
<td>Resilient Backpropagation</td>
<td>trainrp</td>
<td>RBP</td>
</tr>
<tr>
<td>Scaled Conjugate Gradient</td>
<td>trainscg</td>
<td>SCG</td>
</tr>
<tr>
<td>Fletcher-reeves Conjugate Gradient</td>
<td>Traincgf</td>
<td>CGF</td>
</tr>
</tbody>
</table>

Figure 5.24 Training results using Levenberg-Marquard Algorithm for node 1

Figure 5.25 show the results of the training, validation and test of the BFGS Quasi-Newton and Resilient Back-propagation algorithms where mean square errors were 2.0342e-007 reached at 6 epochs, and 2.0532e-007 with the best training at epoch 2, respectively. Figure 5.26 shows the mean square error for: Scaled Conjugated Gradient and Fletcher-Reeves Conjugated Gradient algorithms.
Figure 5.25 Training results for node 1 a) BFGS Quasi-Newton algorithm, b) by Resilient Back-propagation algorithm

Figure 5.26 Results of the training for node 1 a) Scaled Conjugate Gradient algorithm, b) Fletcher-reeves Conjugate Gradient algorithm

Figure 5.26 a) shows the training results of the scaled conjugated gradient where the best training was reached at epoch 3 and the mean square error was 4.2496e-007 while Fletcher-Reeves conjugated gradient produced an error of 2.3108e-007 at epoch 3. The procedure was repeated for the 16 nodes and the summary of the mean square errors is
presented in Tables 5.4 and 5.5 for the number of epoch where the best training was reached for every node and by every training algorithm.

Table 5.4 Mean square error by node

<table>
<thead>
<tr>
<th>NODE</th>
<th>Levenberg-Marquardt</th>
<th>BFGS Quasi-Newton</th>
<th>Resilient Backpropagation</th>
<th>Scaled Conjugated Gradient</th>
<th>Fletcher-Reeves C. G.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.89E-07</td>
<td>2.03E-07</td>
<td>2.05E-07</td>
<td>4.25E-07</td>
<td>2.31E-07</td>
</tr>
<tr>
<td>2</td>
<td>3.81E-08</td>
<td>3.62E-07</td>
<td>9.27E-08</td>
<td>7.81E-08</td>
<td>5.90E-08</td>
</tr>
<tr>
<td>3</td>
<td>2.93E-07</td>
<td>7.95E-08</td>
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<td>1.57E-07</td>
<td>9.96E-07</td>
</tr>
<tr>
<td>4</td>
<td>2.19E-07</td>
<td>1.45E-07</td>
<td>1.03E-07</td>
<td>2.13E-07</td>
<td>1.84E-07</td>
</tr>
<tr>
<td>5</td>
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<td>2.16E-07</td>
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<td>2.72E-07</td>
</tr>
<tr>
<td>6</td>
<td>7.46E-07</td>
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<td>3.90E-07</td>
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</tr>
<tr>
<td>7</td>
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<td>9.37E-08</td>
<td>2.02E-08</td>
<td>1.94E-07</td>
</tr>
<tr>
<td>8</td>
<td>8.92E-07</td>
<td>2.11E-07</td>
<td>1.34E-07</td>
<td>3.08E-07</td>
<td>4.27E-08</td>
</tr>
<tr>
<td>9</td>
<td>1.58E-06</td>
<td>3.25E-07</td>
<td>2.36E-08</td>
<td>2.42E-07</td>
<td>4.33E-08</td>
</tr>
<tr>
<td>10</td>
<td>2.10E-07</td>
<td>1.06E-07</td>
<td>5.28E-08</td>
<td>4.32E-08</td>
<td>1.59E-07</td>
</tr>
<tr>
<td>11</td>
<td>1.03E-06</td>
<td>6.08E-07</td>
<td>1.28E-06</td>
<td>8.94E-07</td>
<td>7.02E-08</td>
</tr>
<tr>
<td>12</td>
<td>7.19E-07</td>
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<td>7.11E-08</td>
<td>1.10E-07</td>
</tr>
<tr>
<td>13</td>
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<td>1.12E-06</td>
<td>1.36E-06</td>
<td>1.31E-06</td>
<td>3.50E-08</td>
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<td>14</td>
<td>2.09E-07</td>
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<td>1.39E-06</td>
<td>9.64E-07</td>
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<td>15</td>
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<td>1.63E-07</td>
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<tr>
<td>16</td>
<td>2.08E-07</td>
<td>4.49E-07</td>
<td>6.79E-07</td>
<td>2.70E-08</td>
<td>5.03E-07</td>
</tr>
</tbody>
</table>

Table 5.4 summarizes the mean square error for sixteen random nodes. In general, error in all cases is small, and then the criteria to select the best training algorithm depend on the algorithms that produce better fit with the FE training results. As shown in Table 5.5 the BFGS Quasi-Newton is the algorithm that converges with the best training results with a higher number of epochs. However, the architecture of the neural network considered 200 epoch but all the trainings converged before that limit. The database in this training was relatively small, with 42 data. This can result in a bad fitted curve for particular algorithms because of the limited number of training data while other algorithms provide fairly good results with limited databases. While in this case, the time required for the calculations was less than a minute in all the cases, BFGS Quasi-Newton could be slower with higher database as shown in Table 5.5. The number of epochs represent the time require to converge.
Table 5.5. Maximum number of epochs for the best training

<table>
<thead>
<tr>
<th>NODE</th>
<th>Levenberg-Marquardt</th>
<th>BFGS Quasi-Newton</th>
<th>Resilient Backpropagation</th>
<th>Scaled Conjugated Gradient</th>
<th>Fletcher-Reeves C. G.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>6</td>
<td>2</td>
<td>3</td>
<td>3</td>
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<td>4</td>
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<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>8</td>
<td>3</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>7</td>
<td>4</td>
<td>2</td>
<td>3</td>
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<td>3</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Data were compared and plotted following the procedure described before and reported in the Figures of Appendix 4. They were used to identify the algorithms with the best fit to the FE training values. BFGS Quasi-Newton, followed by Scaled Conjugated Gradient and Fletcher-Reeves are the algorithms that better fit the results from the numerical values. However, all the algorithms have a very small error. The standard deviation calculated to compare the mean square error of every algorithm in the deployment for 16 nodes is shown in Table 5.6.

Table 5.6 Comparison of the standard deviation of the error in the training of five ANN algorithms

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levenberg-Marquardt</td>
<td>4.1334E-07</td>
</tr>
<tr>
<td>BFGS Quasi-Newton</td>
<td>3.2317E-07</td>
</tr>
<tr>
<td>Resilient Backpropagation</td>
<td>4.9894E-07</td>
</tr>
<tr>
<td>Scaled Conjugate Gradient</td>
<td>3.8028E-07</td>
</tr>
<tr>
<td>Fletcher-Reeves Conjugate Gradient</td>
<td>2.9747E-07</td>
</tr>
</tbody>
</table>
Table 5.6 shows that the Fletcher-Reeves algorithm provides the smallest standard deviation while Resilient Back-propagation provides higher variations in the error between every submitted analysis. On the other hand, BFGS Quasi-Newton shows one of the better fits to the FE results and is the second one with the smallest standard deviation.

### 5.5 Results from the numerical analysis of the compression of the talus in babies

The distance between top and bottom plates was calculated based on the difference of the coordinates of the top and bottom nodes used for the mesh analysis of Section 5.3.1. As a consequence, the initial height of the sample from the top to the bottom surfaces was $H_0=12.304$ mm. The maximum compressive displacement applied to the sample was 5 mm which means the sample was compressed 40.51% of its original height.

![Stress-Displacement curve](image)

*Figure 5.27 Stress-Displacement curve*
Figure 5.27 shows the maximum displacement of 5mm in the X axis and the maximum stress resulting from that displacement of 0.0397 MPa at 5mm. The minimum stress was 0.0134 MPa at 1 mm compression. A linear adjustment was applied in order to know the trend of the results in the analysis of every displacement from 1 mm to 5 mm. Table 5.5 shows the values of displacement, stress and strain for the unconfined compression analysis of the talus based on a CT scan geometry. Table 5.7 contains the stress-strain values for the compression of the talus, modelled using CT scans.

*Table 5.7 Results from the compression numerical analysis of talus in babies*

<table>
<thead>
<tr>
<th>Compression (mm)</th>
<th>Max. Misses Stress. (MPa)</th>
<th>Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0134303</td>
<td>0.08103268</td>
</tr>
<tr>
<td>2</td>
<td>0.0182864</td>
<td>0.162065361</td>
</tr>
<tr>
<td>3</td>
<td>0.0245082</td>
<td>0.243098041</td>
</tr>
<tr>
<td>4</td>
<td>0.0294166</td>
<td>0.324130722</td>
</tr>
<tr>
<td>5</td>
<td>0.0397061</td>
<td>0.405163402</td>
</tr>
</tbody>
</table>

Figure 5.28 shows in blue the values for the Stress-Strain for every displacement and a linear relationship was fitted to the data. The values for the strain were calculated for every displacement and shown in Table 5.7.

*Figure 5.28 Stress vs Strain curve*
Figure 5.29 shows the stress distributions on the side of the compressed talus at 5mm displacement assembled with two analytical plates and the general stress values including the plates. The Z axis is the one used for the applications of displacements. Figure 5.32 shows a wider view of the stress patterns in the talus in different areas, without plates for more accuracy in the results.

**Figure 5.29 Stress distributions at 5mm compression displacement**

**Figure 5.30 a) maximum displacement and, b) maximum stress at 5mm compression**
Figure 5.30 shows in: a) the initial and final displacements and deformations in the talus. The maximum displacement analysed in the current analysis was 5mm where the zone with the maximum deformation is due to the compression of the upper face of the bone. \( P_{T1} \) represents the upper plate at its starting position while, \( P_{T2} \) is the same upper plate at the final position after compression. The intermediate line is the maximum displacement point reached during the compression numerical analysis. Figure 5.23 B) shows the results of the maximum stress at 5mm displacement. The intermediate line describes the point of maximum compression and the plate in the upper plate shows the original dimensions of the talus. As the units of the models are in mm, the maximum von Misses stress value at 5mm compression is 0.39MPa.

\[ \text{Figure 5.31 Maximum displacements at 5 mm compression in X, Y and Z axes} \]

Figure 5.31 shows the displacement levels in the different axes where Figure 5.31 (c) shows the maximum compression applied in the Z axis as 5mm. It should be noted in this Figure that the top plate starts at \( P_{T1} \) and reaches \( P_{T2} \) when the maximum compression has been applied. The maximum displacement in the X and Y axes are 1.91 mm and 1.75 mm, respectively. Displacements in Z are greater because that is the reference compression axis. These values give a panorama of the deformation of the bone in the X and Y axes as a result of the compression of 5 mm in Z axis.
Figure 5.32 displays the stress in different views of the bone at the maximum compression in the current analysis. The top and the bottom have some of the highest stress concentration zones as a result of the contact with the compression plates.

### 5.5.1 Results applied to clinical applications

In Clinical applications, the results can be extended to the analysis of K-wires inside the bone. Many studies have analysed the K-wire behaviour. However, there are just a few studies on the effects of K-wires on the bones and tissues. This clinical aspect is of relevance because it determines the reliability of the treatments and the modifications to the current procedures in clubfoot. Figure 5.33 shows the assembly to analyse the interaction area between the bone (calcaneus) and wires in babies. Reshaping in the contact area was applied in order to perform the mesh.
As an extension of this study, the analysis of the K-wires inside the bones enables to determine the safety of the procedure applied to babies. Figure 5.34 shows the assembly of the K-wire and the calcaneus of a baby. The bone was modelled used CT scans. The wires using software design such as Autodesk Inventor 2012.
Figure 5.35 Stress distributions around the wire-bone area

Figure 5.35 shows the stress distribution in the contact area of the calcaneus of a baby and the K-wire commonly used to fix the Ilizarov fixator. The Figure shows stress around the hole which is dependant to the displacement levels of the wires.

5.6 Discussion and conclusions

Most of the studies that have analysed the body limbs have been carried out in adults. In the case of the foot, the literature reports models to investigate the mechanical properties of the foot tissues in normal subjects as shown in the review of Chapter 3. Some studies analyse pathological subjects. However few analyses focus on the mechanical properties of kids and babies. This is highly important, because the first attempts to treat particular pathologies start in the very early development stages in childhood and few months after birth. Failure in this early treatments leads to relapse cases or the development of further pathologies. In the investigation on the use of the Ilizarov frame to treat clubfoot; many aspects of the literature are still unknown. Data about the mechanical properties of normal baby's tissues and clubfoot tissues are still vague and the literature is limited. This makes it difficult to analyse for specific pathologies. An attempt to contribute to this analysis was made in order to investigate the mechanical behaviour of the talus that is one of the most affected bones during clubfoot correction (Dobbs et al., 2000). This is the first study providing numerical data on the mechanical behaviour if the talus in clubfoot babies. There is no literature on
mechanical test on the baby’s talus reports the yield strength. Therefore, an approximate value of yield strength was determined. This is a critical value in order to establish the maximum compressive load to be applied to the talus during the correction to avoid plastic deformations in the talus. Then, one of the limitations is that establishing a maximum compression range depends on the yield strength. However, in the current analysis, the yield strength was estimated using the 0.2% criteria based on the experimental data reported by Mahmoodian et al. (2009).

Results from this study can be used to analyse the existing corrective procedures for clubfoot babies younger than 6 months old in order to avoid plastic deformations in their bones. Subsequent studies on the analysis of the frame applied to clubfoot babies are suggested to consider the mechanical behaviour of the bones in babies rather than values from adults. The current study provides the stress patterns in the talus of babies due to compression, which is one of the most deformable bones during clubfoot correction. Corrective procedures are suggested to increase the time of correction by reducing the displacements to avoid plastic deformations in the bones. In the case of the Ponseti’s method, it is suggested to provide correction by increasing the number of casts and reducing the level of displacement during the correction based on the proof stress value obtained in this thesis. In the Ilizarov procedure, it is suggested to provide correction by smaller displacements at least in children.
CHAPTER 6

Identification of the main stressed areas in single rod displacements arrangement on the Ilizarov frame

6.1 Introduction

Ilizarov fixator has been applied in different pathologies considering that its first applications were on fracture, bone lengthening and deformities corrections (Dobbs et al., 2009). The important factor is that those applications were focused on limbs which involve the corrective procedures applied to long bones such as femur and tibia. After the success achieved with the frame, further applications were considered. One of those is the correction of deformities in the foot and ankle for different pathologies. Clubfoot is one of the most complex pathologies to treat in the foot because it includes four components: varus, equinus, cavus and adductus. Then, it requires repositioning 26 bones of the foot into a normal foot by means of various adjustments of the Ilizarov fixator. Some studies have analysed the frame and wires applied to the tibia and fibula corrections (Paley, 1994; Bronson et al., 1998; Watson et al., 2000; Davidson et al., 2003; Zhang G, 2004; Watson et al., 2007; Zamani & Oyadiji, 2008). Although some studies report the efficiency of the treatment, there are clinical reports with a high percentage of failure. One of the causes of the failures can be attributed to the lack of procedures and analysis on the frame applied specifically to clubfoot.

The application of the Ilizarov frame to treat fractures usually involves two separated bones to be linked in the desired position then, the correction of deformities requires modifying the position of the two bones in order to achieve the right angle between them. On the other hand, clubfoot involves repositioning 26 bones with different angles
between each part of bones in order to achieve a normal foot where the most critical area is the ankle joint. Another complexity in the correction is that clubfoot tissues around the foot and ankle including ligaments, tendons, and muscles, are positioned in different directions and depending on the severity; the stiffness in the foot and ankle can vary from patient to patient. Relapsed cases and adult patients to be treated with Ilizarov frame, usually have stiffer soft tissues than babies in general. This highlights the main difference between treating babies, infants and adults because the mechanical properties of their tissues are completely different. In addition, the amount of ligaments and tendons to link the 26 bones of the foot is higher than those found in other limbs.

As reported in previous Chapters, one of the main problems when applying the Ilizarov frame in the corrections of lower limbs is the lack of a proper methodology to adjust the frame. The fixator presents a high redundancy (big number of adjustments) if it is analysed as a mechanism for the reason that it was not designed to work as a mechanism but as a structure during the correction. Nevertheless, it has multiple possibilities to perform different assemblies and adjustments due to the multiple parts it has on the lower frame assembly. This depends on every limb and pathology. There are 3 principal factors that can affect the proper deployment of the frame: 1) the mechanical properties of the frame parts and the frame assembly configuration, 2) the pathology to apply the frame to which determines the configuration of the frame assembly that can be readjusted according to the severity determined in the assessment, 3) the proper assessment of the severity to determine the right directions and an adequate treatment. Poor results and relapsed clubfoot cases usually are caused by one of these factors. In the process of correction it is essential to identify the parts and sections to be gradually adjusted however, the mechanical properties of the frame under these adjustments has not yet been analysed. Then, it is necessary to ensure the better deployment of the fixator in order to achieve the best possible results. Nowadays, surgeons depend on their own experience to perform adjustments. For those reasons, results in many papers refer to relapsed clubfoot cases and a considerable high percentage of failure after the treatment. This could be due to the improper procedures for adjusting the frame during the correction and the factors that have been previously mentioned.

One of the inconveniences when adjusting the rods of the fixator is its bending. This results when performing adjustments in rods without releasing adjustments in other rods.
and frame connectors. As a result, rods plastically get deformed and further adjustments are complicated. Also, rings can present in particular cases breakage in the connecting hole areas. Although this is uncommon, in the clinical practice happens. The remarkable issue is that when the assembling the frame of bending of the rods has been reported, even if the frame has not been placed on the foot and ankle. This is due to an improper adjustment of the frame which exceeds its adjustment limits rather than the induced stresses produced from the foot to the frame.

Compared to the Taylor Spatial Frame (TSF), Ilizarov fixator has more flexibility in the adjustment but at the same time it has a higher level asymmetry in the assembly resulting in more complex assemblies. TSF is able to perform millimetric adjustments which have been applied to correct the rotation between bones by adjusting the angles between two bones. There are some analyses on the application of the TSF to the tibia but there are no applications of the TSF in clubfoot. This is because clubfoot requires adjustments in different directions which TSF is not able to easily perform.

As it has been mentioned, there is not a precise methodology for the adjustment of the frame and it is essential to contribute to the methodology in order to achieve better results in the process of correction. Therefore, the aim of this study was to identify the highly stressed areas of the frame in order to identify the main components of the frame that require to be adjusted when displacing a single rod as part of the clubfoot correction. This was considered as the starting criterion to analyse the adjustment procedures of the frame because the most critical stress condition occurs when a single rod is displaced while the adjustment of other rods and connectors are fixed. In further researches, different combinations of rods adjustment can be modelled based on the identification of the highly stressed areas resulting from the adjustment of single rods.

Figure 6.1 shows the assembly applied for clubfoot correction of children. It is possible to observe a different angle in the bones as well in the frame frontal ring and rods. Bending in one of the frontal rods is noticeable. Finally, it is important to consider that the main objective when applying the Ilizarov fixator is to obtain the best possible results during the correction with less possible side effects and relapse. Then, it is necessary to guarantee that the general stresses induced in the frame is under the yield strength values because of two reasons: 1) if the frame generates stresses on it structure
due to improper adjustments, it becomes less efficient due to bending of the rod and, 2) if the adjustments are not made in the right areas, it can require major and further adjustments which can cause plastic deformations. That is the reason to analyse and identify the highly stressed areas in order to propose a further adequate methodology for the adjustment of the frame during the correction process. In the current Chapter, the methodology to achieve the identification of the highly stressed areas by the displacement of four adjusting rods one by one is described in this Chapter, as well as the results of the current analysis. Figure 6.1 shows an Ilizarov frame from a patient.

Figure 6.1 Ilizarov frame during a clubfoot correction
6.2 Methodology for the identification of stresses in the frame applied to clubfoot

A numerical model of the Ilizarov frame was created in order to analyse the highly stressed areas along the frame by displacing independent rods. The design of the parts to create the fixator assembly was made on Autodesk Inventor 2012 and it was developed under the characteristics of an adult clubfoot assembly. The analysis was based on the assembly proposed by Kirienko et al. (2003) for complex foot deformities correction. Also, it was based on the guidance of an experienced surgeon on the application of the frame to treat clubfoot. The modelling procedures follow the same criteria described on Chapters 4 and 5 to create the assembly of the 3D model of the frame. The assembly was imported into the Finite Element software, Abaqus 10.0 where the meshing, boundary conditions, loads and constraints were applied.

As described in Chapter 3, the assembly consists of 2 main Sections: a) the tibiofibular upper assembly, and b) the foot and ankle lower assembly. In the current model, four rods and two full rings were merged in order to make a single rigid part. In addition, nuts were suppressed from the assembly and tie constraints were established and holes were excluded from the rings to reduce the model complexity. Just the holes to fix main rods and connectors were modelled. Also, the upper section of the frame was merged because the section that is constantly modified is the lower section. Then, the analysis was focused on the stresses on the foot and ankle lower section of the frame. Four rods were gradually displaced by intervals of 0.25mm up to 6 mm. This was considering that in the clinical practice, the common adjustment is by 1mm displacement per day at intervals of 0.25mm four times a day (Grivas and Magnissalis 2011). Two frontal rods, one lateral rod and one back rod which are tested and labelled as rod 1, rod 2, rod 3 and rod 4 as shown in Figure 6.2 (b). This is because they are the main rod to perform the major corrections of the clubfoot components involving the ankle and the current
Chapter 6 Identification of the main stressed areas in single rod displacements arrangement on the Ilizarov frame

research focused on the effects on the ankle joint area. Threads on the rods were omitted as well to simplify the model.

Figure 6.2 a) example of an in vivo clubfoot assembly with a sawbones model inside, b) 3D model of the lower limb and the Ilizarov frame

The model in Figure 6.2 (b) was based on the assembly presented by Kinirenko et al. (2003) and shown in Figure 6.2. It is important to remark that there are different variations on the frame assembly according to the different pathologies and the surgeon’s directions. The referred model is the basis for the corrections of lower limb pathologies and was considered as the first analysis approach. Also, it shows the frame components in fully corrected foot position. Then, an inverse analysis was carried out from a normal foot assembly by displacing a rod to simulate a clubfoot position. Beside the rods of Figure 6.2 (b), the numbers (in red colour) identify the four different rods modelled in the current analysis.
Figure 6.3, describes the assembly proposed by Kirienko, (2003). The rods analysed in the model are shown as rod 1, 2, 3, and 4. Once the geometries were designed and assembled in Autodesk Inventor 2012, the model was imported to PowerSHAPE 2010 to verify the geometries for errors and to convert the *.iges and *igs extensions to *.sat files. Then, the model was imported to Abaqus 6.10 to carry out the FE analyses. The position of the imported geometries is exactly the same as the original file created in Inventor. In addition, the dimensions of the frame components are preserved by Abaqus. The units of the length for the modelling of the parts were mm, and, mechanical stress properties were defined in MPa. The decision to create the parts in design software such as Inventor instead of Abaqus, is because Inventor is a CAD-oriented modelling software. Then, modelling is faster and less complicated in a dedicated design software rather than Abaqus. Rings and half rings of 150 mm and 6 mm rods were used to model the frame.

The frame was modelled with mechanical properties with typical values for stainless steel with a Poisson’s ratio value of $\nu=0.3$ and a modulus of elasticity of $E=210\mathrm{GPa}$.
Interactions were declared as hard contact normal behaviour and frictionless tangential behaviour as in previous analyses of the frame in the literature (Zamani & Oyadiji, 2010). This is also because displacements were going to be applied in order to analyse the stresses of the fixed parts of the frame as a function of the displacement of independent rods. The design of the frame required four interaction properties (surface to surface contact) applied to the four rods to be displaced where the master surface was the rod and the slave surface the connector where the rod was displaced. Twenty four (24) interactions between the rods, rings and connectors were modelled, including the rods with their respective connectors. Also, five boundary conditions were applied where four of these are the displacements of the rods and part (upper assembly) is constrained by encastré Boundary conditions (BC). For the boundary conditions applied to the rods, a datum coordinate system was placed at the top of the rods. This was created based on datum axis along a rod and the surface of the end of the rod. This condition was considered to apply the displacement in the rod direction and avoid the displacements in different axes.

Constraints, interactions and boundary conditions were established in every rod variation. Then, when a rod was displaced, the corresponding tie constrain was suppressed, the interactions on the rod were activated and the boundary conditions on that specific rod were applied. The remaining elements were constrained in order to model a single rod displacement. This methodology allowed to performed changes in the rods to allow displacement or to tie the parts depending on the arrangement to be analysed. Displacement boundary conditions were modified with different displacement values from 0.25 mm to 6 mm at intervals of 0.25 mm as mentioned before. Non-linear geometry (NLGEOM) was declared in the step to consider the effects of large deformations and displacements. As the current analysis was based on the displacement of the rods, this is an essential condition for the current analysis. Figure 6.3 shows the boundary conditions applied to the assembly.

Figure 6.3 shows the boundary conditions applied to the 3D frame model. Figure 6.4 (a) shows the coordinate axes to apply boundary conditions of displacement on the top of every rod. The interaction properties of one single rod (rod 2) are highlighted in red colour. Figure 6.4 (b) shows the encastré Boundary conditions (BC) area of the upper
assembly of the frame, the foot geometry built up from CT scan images, and the comparison of the dimensions of the frame with the real adult foot.

Figure 6.4  a) Coordinate axes for the displacements b) upper assembly (encastre)

Because, the procedure consisted of analysing different levels of rod displacements one by one, the rest of the structure was totally constrained in order to identify the highly stressed areas produced by the displacements on the rods. Table 6.1 summarises the displacement applied to the independent rods.

<table>
<thead>
<tr>
<th>Displaced Rod</th>
<th>Unconstrained components</th>
<th>Displacement Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rod 1</td>
<td>Rod 2, 3, 4 and Structure</td>
<td>0.25 to 6 mm</td>
</tr>
<tr>
<td>Rod 2</td>
<td>Rod 1, 3, 4 and Structure</td>
<td>0.25 to 6 mm</td>
</tr>
<tr>
<td>Rod 3</td>
<td>Rod 1, 2, 4 and Structure</td>
<td>0.25 to 6 mm</td>
</tr>
<tr>
<td>Rod 4</td>
<td>Rod 1, 2, 3 and Structure</td>
<td>0.25 to 6 mm</td>
</tr>
</tbody>
</table>

The model was meshed using the C3D4 tetrahedral Abaqus element type. The decision to consider this element instead of hexahedral elements is because of the complexity of the model and to reduce the time to run every analysis. In addition, C3D4 elements have
less number of nodes compared with second order elements and conventional hexahedral elements. However, C3D4 elements can give accurate results using a fine to very fine mesh. A mesh sensitivity study was performed to the model.

Figure 6.5 shows the results of the mesh sensitivity study where, as expected, the convergence zone of the tetrahedral elements requires a fine to very fine mesh in order to produce minor variations as functions of the number of elements. The number of elements in the current model was 126520 which produced a very fine mesh free of distorted elements with warnings by verifying the mesh with the verify mesh tool in the Abaqus mesh module. The convergence occurred with over 90000 elements in this model.

![Figure 6.5 Mesh convergence study of C3D4 Abaqus elements in the Ilizarov Frame 3D mode at 2 mm displacement.](image)

Figure 6.6 shows different mesh densities tested in the model. The coarse mesh produces distorted elements with angles less than 45° and greater than 135°, mainly in the rings. Fine and very fine meshes provide homogeneity of the element size. Also fine to very fine meshes provide small variations in the results of the mesh analysis. The mesh selected for the current model was a fine mesh to reduce the variations in the results because of the well-known behaviour of these elements compared to hexahedral and second order elements. This, way, the computation time reduces providing relative accurate results and eliminating distorted elements produced by sharp edges in the elements.
Chapter 6 Identification of the main stressed areas in single rod displacements arrangement on the Ilizarov frame

Figure 6.6 Different mesh densities
6.3 Result analysis

The FEA results obtained are shown in Table 6.2 and Figure 6.7. The stress contours in the figures show the V. Misses stress distributions in the frame components. The results show the highly stressed areas as the result of displacing every independent rod.

![Figure 6.7 Maximum stresses induced in the frame as a function of the level of displacement of the rods.](image)

Figure 6.7 shows the maximum V. Misses stresses as a function of the increment of the displacement in the four main rods. The Figure shows that Rod 2 presents the higher stress levels as a result of the same displacement levels, compared to the other three rods. On the other hand, Rods 1 and 3, present smaller stress levels compared to Rod 2 and Rod 4. Also, the Figure shows a similar behaviour under the same displacement conditions. Rod 4 presents a similar behaviour up to about 4 mm displacement. However, the stress increases probably due to a stress concentration in a connector. The Figure shows that Rod 2 and 4, exceed the yield strength of stainless steel of 520MPa (Beer et al., 1974; Zhang, 2004; Zamani & Oyadiji, 2010) at displacements above 4.25mm. Rod 1 induces stress levels in the frame at displacement above 5.25mm, rod two at 4.25mm, rod three 5.5 mm and Rod four at 4.25 mm. Table 6.2 shows the relation of the stress and displacement.
Chapter 6 Identification of the main stressed areas in single rod displacements arrangement on the Ilizarov frame

Table 6.2 Stress as a function of the displacement in four main Ilizarov rods

<table>
<thead>
<tr>
<th>Displacement (mm)</th>
<th>Rod 1</th>
<th>Rod 2</th>
<th>Rod 3</th>
<th>Rod 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>26.5946</td>
<td>28.4937</td>
<td>22.7625</td>
<td>24.9016</td>
</tr>
<tr>
<td>0.5</td>
<td>53.1861</td>
<td>57.036</td>
<td>45.4983</td>
<td>50.4782</td>
</tr>
<tr>
<td>0.75</td>
<td>79.7777</td>
<td>85.9446</td>
<td>68.2068</td>
<td>75.0399</td>
</tr>
<tr>
<td>1</td>
<td>106.35</td>
<td>115.089</td>
<td>91.2832</td>
<td>99.8596</td>
</tr>
<tr>
<td>1.25</td>
<td>132.926</td>
<td>144.301</td>
<td>115.871</td>
<td>125.931</td>
</tr>
<tr>
<td>1.5</td>
<td>159.612</td>
<td>175.19</td>
<td>140.823</td>
<td>150.06</td>
</tr>
<tr>
<td>1.75</td>
<td>173.892</td>
<td>204.479</td>
<td>165.944</td>
<td>177.554</td>
</tr>
<tr>
<td>2</td>
<td>198.607</td>
<td>233.79</td>
<td>191.089</td>
<td>201.936</td>
</tr>
<tr>
<td>2.25</td>
<td>223.29</td>
<td>262.895</td>
<td>200.812</td>
<td>225.972</td>
</tr>
<tr>
<td>2.5</td>
<td>247.941</td>
<td>289.118</td>
<td>223.072</td>
<td>251.368</td>
</tr>
<tr>
<td>2.75</td>
<td>272.559</td>
<td>321.262</td>
<td>246.359</td>
<td>276.6</td>
</tr>
<tr>
<td>3</td>
<td>297.143</td>
<td>351.161</td>
<td>269.782</td>
<td>302.451</td>
</tr>
<tr>
<td>3.25</td>
<td>321.695</td>
<td>381.125</td>
<td>293.544</td>
<td>328.639</td>
</tr>
<tr>
<td>3.5</td>
<td>345.983</td>
<td>411.167</td>
<td>316.753</td>
<td>356.829</td>
</tr>
<tr>
<td>3.75</td>
<td>369.474</td>
<td>441.414</td>
<td>340.323</td>
<td>388.469</td>
</tr>
<tr>
<td>4</td>
<td>393.965</td>
<td>471.849</td>
<td>391.471</td>
<td>408.403</td>
</tr>
<tr>
<td>4.25</td>
<td>418.547</td>
<td>502.053</td>
<td>416.848</td>
<td>472.115</td>
</tr>
<tr>
<td>4.5</td>
<td>440.951</td>
<td>532.16</td>
<td>422.343</td>
<td>495.358</td>
</tr>
<tr>
<td>4.75</td>
<td>463.095</td>
<td>562.48</td>
<td>446.899</td>
<td>523.512</td>
</tr>
<tr>
<td>5</td>
<td>485.187</td>
<td>592.867</td>
<td>471.266</td>
<td>553.678</td>
</tr>
<tr>
<td>5.25</td>
<td>507.028</td>
<td>624.91</td>
<td>495.556</td>
<td>585.058</td>
</tr>
<tr>
<td>5.5</td>
<td>528.769</td>
<td>654.499</td>
<td>519.998</td>
<td>616.68</td>
</tr>
<tr>
<td>5.75</td>
<td>550.859</td>
<td>680.802</td>
<td>544.495</td>
<td>647.81</td>
</tr>
<tr>
<td>6</td>
<td>572.446</td>
<td>720.906</td>
<td>568.983</td>
<td>685.351</td>
</tr>
</tbody>
</table>

The results show the most critical condition from a design perspective which is, when the full frame is unconstrained and just a single rod is displaced. However, in the clinical practice, there connectors are enabling to be adjusted. However, there is not a right procedure to date, because it depends on the experience of the surgeon. The current Numerical analysis enables to identify the associated connector to be adjusted as a function of the displacement of the four main rods. In addition, the results show that adjusting the independent rods more 4.25 mm lead to plastic deformations in the
components of the frame. Figures 6.8 to 6.12 shows the maximum stresses on the frame as the result of 4.25 mm displacement, which is in general below the yield strength of the frame.

Figure 6.8 describe the stress distributions produced by 4.25 mm displacement of rod 1. Main stressed areas were identified as rod boxes from (a) to (g). It is possible to notice a correlation between the displacement in (a) and the stresses induce in (e) and (h) who corresponds to rod 2 and rod 3. However, the maximum stressed area is identified in (f) area, in the connection between the half ring and rod 2. Areas (b), (c) and (d) are highly stresses in the connectors. The connectors associated with those areas are expected to be adjusted to reduce stresses and increase the efficiency of the frame. Also, Figure 6.7 shows one of the paths to the right adjustment procedures which involves that, displacing rod 1 implicates releasing stress in rod 2 on the contrary direction. This is to
avoid bending and plastic deformations of the frontal rods, as shown in Figure 6.8. Also, breakage and bending of ring can happen due to stress concentrations due to improper adjustments procedures for this frame configuration. The area between the connectors of rod 2 and the half frontal ring are the highly stressed areas. Displacements above 4.25 can produce plastic deformations in the frame components when the right connectors are improperly adjusted.

Figure 6.9 shows the frontal section of the Ilizarov frame applied to correct clubfoot. This part of the frame was used by an experienced surgeon at NHS. The picture displays bending in Rod 1, and partial bending of rod 2 which is due to an improper adjustment of Rod2 1 and 2. This clearly shows the interdependence of the two rods. The bending
in Rod 1 is identified by two straight lines, which highlight the plastic deformation of the rod.

Figure 6.10 Stresses produced by 4.24 mm Displacement in rod 2.

Figure 6.10 shows the highly stressed areas in the frame at 4.25 mm displacement of rod 2. The interdependence between the frontal rods (rod 1 and rod 2) is evident in this figure. Section (a) and (b) present high stresses between the rod connectors. This can lead to plastic deformations produced by improper adjustment procedures. Area b presents stresses, similar to those as displacing rod 1. Area (c) shows stresses in the half ring, similar to those in Figure 6.8. Connectors in (e) present less stresses. However, the maximum stresses are reflected to d area where the maximum stress is located. This means that it is necessary adjusting the connectors in that area, in order to avoid plastic deformations in the frame components. Adjusting the connectors to the identified areas can reduce the stresses in the frame.
Figure 6.11 Stresses produced by 4.24 mm Displacement in rod 3.

Figure 6.11 shows the stresses produced by 4.25 mm displacement in rod 3. The results show that the highly stressed area is located in the same connector area (e) as those patterns presented by the displacement of rod 2. (a) Area shows high stresses in the frontal connector. This is a similar behaviour as the one described by the displacement of Rods 1 and 2. These points out that probably stresses would reduce in that area by reinforcing the assembly in (a). Also, there is an interrelation between rod 3 and rod 4. This is reflected in the stress concentrations in the rod 4, identified by (g) area.
Figure 6.12 shows the highly stressed areas produced by 4.25 mm displacements of rod four. The interdependence reflected by the displacement of rod 3 is shown in this picture. The maximum stress at 4.25 mm produced by rod 4 in the frame is 472 MPa. Areas (g) and (d) are the two main stressed areas in the frame. Also, there are slight stresses in the connectors of (e), (c) and (b) areas.

The results show the most critical adjustment which is when a single rod is adjusted. Then, combinations of rods adjustments require the release pf adjustment in the connectors related to the identified areas.
6.4 Discussions and conclusions

The model presented in this Chapter represents an advance in the knowledge about the corrective procedures for clubfoot using the Ilizarov Technique. The current 3D model was developed in order to analyse and contribute to the understanding of the Ilizarov Fixator adjustment applied to clubfoot and lower limb pathologies. The presented results enable the identification of connectors related with the highly stressed sections that must be adjusted when one of the four modelled rods are displaced.

Nielsen et al. (2005) suggest that individual adjustments of the rods in the frame can lead surgeons to control the behaviour of the frame by the superposition of different designs and adjustments. However, they did not analyse nor tested this suggestion. This suggestion was considered as a starting point to the analysis presented in this Chapter.

In the normal practice, applying the Ilizarov technique results in bending of rods and less common but possible rupture of the frame rings has been founded. This suggests an improper adjustment of the frame which can generate higher stresses during clubfoot correction, reducing its efficiency in clinical practice. For the purpose of this analysis; bones were excluded from the model. Foot and ankle bones were used as a reference for the assembly but not load generated from the foot was induced on the model. This methodology allows analysis of the possible stresses that can cause an improper adjustment of the frame and it provides guidance for the corrections performed by surgeons depending on the pathology and the severity of every case.

Ilizarov fixator functions as a structure when is placed on the foot. The majority of the time which is during the correction, the frame is a rigid structure. During the corrections performed from time to time and determined by the surgeon’s assessment, the frame is adjusted by displacing the correcting rods. However, it is necessary to observe the connectors, rods and parts associated with the displacement of every specific rod in order to do not exceed the adjustment range of the frame.

There are different variations of the assembly for the lower limb. It depends on the pathology and the parts used for its assembly. The geometry, taken as a reference is the one proposed by Kirienko et al. (2003) which is applied in the lower limbs corrections.
Chapter 6 Identification of the main stressed areas in single rod displacements arrangement on the Ilizarov frame

The frame provides a high flexibility to perform adjustments but at the same time, it has a high redundancy when performing adjustments. The methodology, where every single rod displacement is analysed, was considered because, every single pathology demands the adjustment of different rod combinations. The stress patterns identified in the current study will enable the surgeon to perform those different adjustments keeping in consideration the elements subjected to stress in order to release adjustment of connectors during the corrective procedures in order to avoid plastic deformations of the frame components.

The complexity of the model remains in the high number of pieces for the assembly, so that; the number of interactions increases with the number of pieces making the analysis more complicated as well as the different possible assemblies to be tested. In the current analysis, displacement from 2 mm to 2 mm were modelled. The reason for this range is because the normal displacement adjustment is about 1mm by every correction time. Two (2) mm displacements are enough to identify the main highly stressed connectors and components that must be adjusted at the same time that any independent rod is adjusted. The critical stress condition in the frame is when all the elements are tied and just a single one is allowed to be adjusted. This is because releasing displacement on the contrary direction of the adjusted rod releases the stresses in the frame. However, independent rods analysis was established as a first approach to analyse the right adjustment procedures because suggested combinations are carried out due to the experience of surgeons. However, there is not numerical and experimental analysis to validate that these are the right procedures.

Considering that, an objective of the study was to identify the highly stressed areas associated with the displacement of every independent rod when performing adjustments so that, in order to identify it, is not necessary to perform long displacements adjustments. This is because the highly stressed areas are clearly identified with smaller displacements.

The decision to analyse systematically adjustment of independent rods is to estimate the maximum displacement the frame can be subjected to before producing plastic deformations. In clinical practice, the adjustment of several elements including other rods is carried out. However improper adjustments are commonly done resulting in
bend. This individual rod analysis produces two contributions. The first one is to estimate the maximum the rods can be subjected to without causing plastic deformations to the frame components. This is important because bent rods make it difficult subsequent adjustments. The second one is that based on the highly stressed areas, it is possible to identify the associated connectors that need to be released when adjusting any rod.

6.5 Summary

The current Chapter presents a 3D model of a lower limb Ilizarov assembly applied to clubfoot. The model presents the result of the variation of the displacement of four of the main rods applied in the clubfoot corrections. The first part of this Chapter describes the importance of the current analysis based on previous studies. The main studies on the Ilizarov frame have been made, basically to analyse the mechanical properties of the elements of the frame and the assemblies for bone lengthening, fractures or diverse corrections between two bones in long limbs such as tibia. This model represents an advance in the analysis of the clubfoot pathology, as well is the first 3D model presented in the current literature to analyse the fixator in lower limbs applications.

Characteristics of the methodology of the model have been described in this Chapter specifying the reaches and limitations of the model. Reductions in the model has been described in this section in order to achieve reliable results according to the objective which is to identify the highly stressed areas of the frame produced by rods displacements. It is useful to identify the areas and connectors which must be adjusted at the same time a rod is adjusted. This provides useful in formations to surgeons about the adequate adjustments of the frame during the process of correction.

Results are described for Rod 1, Rod 2, Rod 3 and Rod 4, as described in the Figures. Finally, discussions and conclusions about this study are presented in the current Chapter.
7.1 General Discussions

The foot is a very complex structure from the biomechanical perspective. As described before in different Chapters of this thesis, it contains a huge amount and different types of soft tissues, making it complex to be analysed. The literature reports great efforts to model a normal foot, in order to understand its mechanical properties and its biomechanics and also to understand the differences between a healthy and normal foot, in comparison with a pathological foot. Due to its complexity, it is difficult to develop models containing all tendons, ligaments, muscles, veins, cartilages and other soft tissues apart from bones. Therefore, the models reported in the literature commonly aim to investigate isolated elements, or very specific variables in very specific conditions. These simplifications enable to build up a general knowledge of the foot by means of independent analyses, focused on different elements of the foot.

Clubfoot has differences compared to a normal foot in the stiffness of all the constituent tissues and the position of the bones. However, the literature on clubfoot tissues is even more limited in comparison to a normal foot. This lack of literature on the mechanical behaviour of the foot under clubfoot pathology is one of the first limitations to performing analyses as there are changes in the stiffness of the soft tissues. In addition, the Ilizarov technique is a very specific treatment for clubfoot with a very specific range of application. It is used mainly in relapsed clubfoot cases where conventional treatments have failed as the first treatment approach, and in severe clubfoot cases, where the soft tissues present a high stiffness. This is especially true for people born with clubfoot but who were treated when they became adults. In both cases, there is often difficulty in the clubfoot correction using conventional methods.
There is vast literature on the analyses of the independent frame components and the Ilizarov frame applied to bone lengthening and fracture but very limited literature on the frame applied to clubfoot. As a consequence, the analysis of the foot, in a very specific pathology, clubfoot, with a very specific treatment, represents a higher challenge to determine: a) the variables to perform the analyses, b) the methods to perform those analyses. This is because the requirements for different types of physical data, such as the mechanical behaviour of the soft tissues, much of which is not available in the literature, impose limitations on the analyses that can be performed. In the case of the study of the talus presented in the thesis, the mechanical properties of the talus in babies are crucial. The limited literature on that topic represented a challenge. Also, the general literature on the mechanical properties of a) the foot in babies, and b) clubfoot babies, is very limited. This limitation makes it difficult to develop reliable numerical models for clubfoot in babies.

Due to the limitations highlighted above, foundational work was carried out in the thesis to analyse the Ilizarov frame for the treatment of clubfoot pathologies. This involved the development of a 3D model for clubfoot based on the use of CT scan images obtained clinically. The second foundational work carried out and reported in the thesis the analysis of the talus in babies due to the important role of this bone for clubfoot corrections. These two pieces of foundational work constitute the main objectives of the thesis. In order to achieve those objectives, the thesis required a specialised literature review on: a) the anatomy, pathologies and treatments of clubfoot, and b) the mechanical analyses related to the frame and the foot tissues. The first part of the literature review, which was presented in Chapter 2, had the purpose of providing a brief and basic understanding of the medical terminologies, foot anatomy and clubfoot pathologies. This review enabled to determine the most appropriate methods for FE modelling of the frame, in general, and the foot/clubfoot, in particular. The second part of the literature review, which was presented in Chapter 3, is to have a deeper knowledge of the modelling techniques and current analyses performed in this research area and also to determine the appropriate modelling techniques.

It is important to state that, although, the review of the literature presented in the thesis on those topics is extensive, it is still very basic compared to medical books and literature. However, the purpose was centred just on clarifying and identifying the
crucial information related to the studies of further Chapters, rather than deeply
describing the full anatomy of the foot and ankle. Furthermore, as a multidisciplinary
thesis, this literature review was crucial and necessary. On the other hand, Chapter 4
covered the general methods, descriptions, literature and steps to achieve the CAD
models analysed in the thesis. This way, the structure of the thesis was designed with
the purpose of providing a clearer description of the thesis, starting from the general to
the particular topics in the later Chapters. This will make the thesis more understandable
to people involved in medicine as well as in engineering.

In relation to the model of the Ilizarov frame, there are many aspects to be considered to
determine the general modelling methods. Firstly, it is important to focus on the gaps in
the medical applications in order to determine which variables to analyse. The two
most relevant factors that affect the final outcomes after clubfoot treatments are:

a) Adequate procedures to perform the correction. In the case of the Ilizarov method for
the clubfoot correction, the mechanical deployment of the frame that involves the
mechanical design, the materials, the main assembly and the procedures to perform the
adjustments are crucial to achieve the best possible outcomes.

b) The assessment stage. This involves the assessment procedures considering the age
of the patient and the history of previous treatments. The determination of the right
treatment as a result of a proper assessment is very important as failures to determine
the right procedures may lead to poor outcomes. Also, at this stage, the severity of the
clubfoot is determined for every patient.

Regarding the assessment stage, there is still a gap in the literature on the assessment
procedures as the current conventional assessment techniques do not consider the
stiffness of the soft tissues. In relation to the first factor (a), the work presented in the
thesis has contributed to the improvement in the knowledge of the mechanical
behaviour of the frame for clubfoot correction and to the improvement of the general
deployment of the frame. As stated before, the literature reports very few studies on the
frame applied to the foot and ankle and the models presented in the literature are 2D
models. In this thesis, a 3D model, which is a better representation of the real assembly
for clubfoot, has been created and analysed.
Also, the frame comprises different components including wires, rings, rods, nuts. Many different combinations and adjustments of these components are possible. This situation makes difficult to determine all the possible adjustments in the frame. The medical literature provides limited guidelines for the adjustments of the components according to the experience of surgeons. However there is still a range of failures leading to poor outcomes in some patients and those procedures have not been corroborated by numerical models or experimental tests. In Chapter 6, a fundamental study was undertaken to determine the methodology to employ for the proper adjustment of the Ilizarov frame. The first approach employed was the adjustment of single rods and the FE analysis of the corresponding configuration in order to determine the critical stresses in the components of the frame. These critical stresses were used as the measure to determine the order in which the fasteners were to be loosened and the rods were to be adjusted.

The Ilizarov frame provides the possibility of configuring completely different assemblies to match with specific conditions of a patient’s pathology. Therefore, it was decided to approach firstly the analyses of the frame for clubfoot treatment, based on a “normal patient assembly”. Afterwards, the rods were displaced individually upward or downwards in order to correct the clubfoot. The base or “normal patient assembly” was the one proposed by Kirienko et al. (2003) for lower limb deformities. The mechanical failure such as bending of rods and breakage of rings in few cases has been reported in the medical practice. The Young’s moduli of an adult’s bone and of the stainless steel (SS) components of the Ilizarov frame are 22 GPa and 210 GPa, respectively. That is, the stainless steel components are almost ten times stiffer than the bone. However, failures of the ring components such as the rods and rings have been observed clinically. These failures raise questions about the role of the adjustment procedures. It is most likely that improper adjustments generate the observed failures of those components instead of the bone. This is relevant because bent rods difficult subsequent adjustments of the frame in clinical practice. For this reason, it was decided to analyse the single frame as foundational work.

This is the first 3D numerical model to analyse the Ilizarov frame applied to clubfoot. The results in the thesis, which are based on single rods adjustment, enabled the identification of the connectors related to the rod displacements at different
displacement levels. This was achieved by identifying the highly stressed sections of the frame. Based on the obtained data reported in this thesis, future analyses can be conducted with multiple rods adjustments by using tools such as Artificial Neural Networks, in order to determine a full systematic procedure for adjusting the rods simultaneously. At the moment, the results presented have medical relevance in providing guidelines for surgeons to follow in the adjustment of single rods in the frame.

The analysis of the talus in babies was based on the CT scans of a new-born clubfoot baby. The mechanical properties were established based on the elasticity modulus and Poisson’s ratio presented in a paper. These material properties are crucial to perform the analyses of the talus in babies. However, most of the numerical analyses and experimental tests reported in the literature have focused on adults rather than children and babies. Nevertheless, it is highly important to study the foot tissues in babies. Usually, the first treatment approach is during the first months of life, for different foot pathologies, including clubfoot. The reason is because the tissues are softer, enabling an easier correction compared to adults’ tissues which are stiffer. There is a vast gap in the literature on foot tissues in babies. Apart from one paper found that presented the characterisation of the mechanical properties of a foetal talus, there were no other papers found on numerical analyses or experimental testing of a baby’s talus. However, such studies of a baby’s talus are important because conventional treatments have been reported in the literature to cause changes in the shape of the talus (Brand et al., 2006). This is relevant, as the stress distribution, due the change of shape of the talus, can results in imbalances and affections of the normal gait causing possible future pathologies. An example is total ankle replacements due to cartilage attrition whose possible causes may include non-corrected previous foot and ankle pathologies. Chapter 5 aimed to increase the understanding of the mechanical properties of the talus in clubfoot babies. The stress-strain characteristics of the talus and an approximate value of yield strength was determined. Those results can be used in further researches to increase the understanding of the tissues in babies and improve the medical procedures.
7.2 Conclusions

The thesis investigated different aspects of the application of the Ilizarov fixator to clubfoot. As it is well known, the nature of the clubfoot pathology involves complex analysis. This is because the foot contains many soft tissues. On the other hand, this is the first time that the Ilizarov fixator is subjected to a numerical analysis for the correction of clubfoot. The respective literature review on the involved topic was done in order to provide a better understanding of the concepts of this multidisciplinary project. Then, the outcomes achieved in the current thesis are summarised as follows:

- Multidisciplinary studies require a proper and deep literature review on both, the mechanical and medical related topics. The current thesis contains the necessary literature review in both areas in order to provide a clearer understanding for professionals involved in medicine and engineering. Also, to determine the right procedures and variables for the FE analyses.

- Most of the literature on the numerical analyses of the foot has focused on adult tissues. As a result, the research in children and babies is limited. The current thesis analysed the talus in babies which is one of the most affected bones during clubfoot correction. Previous studies suggest shape changes of the talus after the treatment of clubfoot (Brand et al., 2006). For those reasons, the current thesis investigated the mechanical properties of the talus subjected to compressive loads by determining the stress patterns in the talus and determining an approximate value of yield strength. These results contribute to the knowledge of the mechanical behaviour of this tissue which can be applied to subsequent studies on the interaction of different bones of the foot and ankle in babies with clubfoot.

- The literature on the mechanical properties of babies is limited. As a result, modelling is subjected to limitations. In the current analysis, the yield strength of the talus and other tissues in babies has not been reported yet. Therefore it was estimated. Experimental studies are required in order to extend the knowledge and provide a consistent applicability in the clinical practice.

- The stiffness of the bones and soft tissues is different in adults, children and babies. In addition, every pathology describes a different mechanical behaviour
of those tissues such as changes in the stiffness of the ligaments. Limitations in the knowledge of the mechanical properties, represent a difficulty the numerical models.

- CT scans are a reliable alternative to model biological tissues. They enable the creation of more accurate models of the bones. As a result, the analysis based on the characteristics of the real pathology by using models based on CT scans; provide a deeper understanding of different pathologies.

- Taylor Spatial Frame and other fixators have been applied in pathologies such as fractures and bone lengthening. However, in the clubfoot application, this frame is not as flexible as the Ilizarov frame. One of the advantages of the Ilizarov frame compared to other fixators is the flexibility to configure different assemblies. However, there are not systematic procedures to determine the right adjustments for clubfoot treatment. Therefore, adjustments still depends on the surgeon’s experience resulting in literature reporting the failure of the technique. The current procedure to analyse the behaviour of the frame subjected to displacement of individual rods, enables to identify, a) the associated connectors to be adjusted as every independent rod is moved, b) the maximum displacement the frame can be subjected to before causing plastic deformations, and c) the interdependence of the adjustment between rods. One of the most recurrent problems in finite element analysis is the reliability of the results. Commonly, a mesh convergence study is performed to establish the convergence zone where results present minimum variations. However, the literature reports studies using similar methodologies but reporting different results. Also, the analysis of biological tissues results in complicated models and depending on the model size, the conventional mesh analysis may require much time. Also ANN can be applied in future studies to analyse different frame configurations.

- There is a vast literature on the clinical aspects that lead to failure of the clubfoot corrective procedures. In the case of clubfoot, most of the analyses have focused on the frame applied to bone lengthening and fractures. Also, the few analyses on the lower limb provide very simple 2D models created with beam elements. The current thesis provides a novel 3D and more complex model of the Ilizarov frame that allows performing different adjustments in order to improve the
deployment of the frame and the accuracy of the analysis with respect to the real frame.

- The novel techniques on modelling of bones enable to perform more accurate analyses. This thesis presented the analyses of the talus of babies based on CT scans of a real clubfoot patient. Compared to studies that model the foot elements based on cylinders or ideal geometries, the real applications in patients require performing analyses based on real tissues geometries.

- A 3D model of the Ilizarov frame was developed and analysed. Also, a 3D model of the talus of a baby, based on CT scans was investigated. Results from the current models are expected to be utilised to improve the corrective procedures and the deployment of the Ilizarov external fixator in terms of adjustments of the frame components during the correction. The analysis of the effects of the compression of the talus is the first path to contribute to the improvement of the Ilizarov technique and other procedures by considering the effects of the correction on the tissues.

- The Ilizarov frame is a complex mechanical device, useful to treat diverse pathologies. There are few models in the literature to analyse the mechanical frame deployment and the failure of its components applied to clubfoot. This thesis studied the possible factors involved in the failure of components by analysing single rod displacements and determining the yield strength of the general assembly. This may contribute to reduce plastic deformations in the rods causing bending. This way, it also contributes to the improvement of the deployment of the frame in clinical applications.

### 7.2 Future works

From the work conducted in this thesis, the following future work is proposed:

- Analysis of the combination of different rods displacements, based on the identified highly stressed areas around the connectors and frame components.
• Analysis of different frame adjustments by implementing Artificial Neural Networks (ANN). After analysing different adjustment combinations, it may be expected to produce a database, with the stress values for different adjustments. Then, to use those data to train Artificial Neural Networks to predict the behaviour of the frame over different adjustments.

• Analysis of the effects of the interaction of the K-Wires with bones of the foot in clubfoot conditions, with mechanical properties of patients with different ages. This analysis will enable to identify the range of applicability of the frame as a function of the age of the patients.

• Developing a novel assessment scale of clubfoot, based on the stiffness of the soft tissues of the foot. The current assessment procedures are orientated to the position of the bones. However, none of them considers the stiffness of the soft tissues, which is an important variable to determine the severity.

• Analysis of the design of the washers and connectors in order to increase the flexibility of the frame adjustments. Some special connectors provide more flexibility in the adjustment. Analysing their impact is an important contribution to the deployment of the frame.

• Establishing a photoelastic procedure to create a novel technique to provide guidance during the correction. A photoelastic frame can be developed and used to identify the relationship between the fringe order and related stress levels. This can provide an alternative to understand the frame behaviour and guide surgeons in the procedures before placing the frame in patients.

• Analysis of the induced stress of the contact area of the talus and calcaneus. This may lead to a better understanding of the deformation rates during the correction of those bones in clubfoot babies to reduce plastic deformations in the bones after correction.

• Analysis of the foot and ankle ligaments including the frame. To be reliable, this will require a complex model of the independent 26 bones of the foot and as
much as possible ligaments in the foot. The current limitation is that the literature reports limited stiffness values of few ligaments obtained by experimental procedures.

- A novel model to analyse the interaction between the talus and calcaneus in babies by determining the contact pressure areas, displacements and stress-strain curves. This can enable the understanding of the limits during clubfoot correction by conventional procedures such as “the Ponseti Method” in order to improve the final outcomes.

- Future studies could analyse the role of the soft tissue stiffness to determine the severity of the deformity. Future works can also consider the analysis of the stresses in the bones of the foot and ankle in babies by applying different displacement levels as a result of casting. Another study can be carried out by analysing the interaction of the bone-wire zone with the Ilizarov procedure in bones of babies.
Prepared to be submitted:


References


The software used for the objectives of this thesis, is listed as follows:

- Abaqus 6.10 to 6.13 versions, from Dassault systems, Simulia
- ScanIP 2.0 from Simpleware
- PowerSHAPE 2012 from Delcam
- Solidworks 2013 from Dassault Systems
- Inventor 2012 from Autodesk.
- Matlab R2013a from Mathworks
Appendix 1. Abaqus coordinates of the random nodes for the mesh sensitivity analysis

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Appendix 2 V. Mises Stress values for 16 random nodes at 2mm compressive displacement for the mesh sensitivity analysis of the talus in babies.

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<td>2592</td>
<td>1.40E-02</td>
<td>2592</td>
<td>9.20E-03</td>
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</table>
Appendix 3 Comparison of the artificial Neural Networks for sixteen random nodes and five training algorithms.

Node 1

Node 2

Node 3
Node 4

Node 5

Node 6
Appendix

Node 16

The diagram shows the stress (MPa) plotted against the number of elements (N. Elements) for Node 16. The line styles and colors represent different optimization methods:

- **Dotted**: S. Mises Node 16 (Levenberg-Marquardt)
- **Dark Green**: (BFGS Quasi-newton)
- **Dark Blue**: (Resilient Backpropagation)
Appendix 4 Matlab codes for ANN.

Thesis codes (talus)

**Levenberg-Marquardt**

```matlab
p=ent';
t=sal';
net=newff(p,t,15);

net.divideParam.trainRatio = 70/100; % training
net.divideParam.valRatio = 15/100; % validation
net.divideParam.testRatio = 15/100; % test

net.trainParam.epochs=200;
net.trainParam.min_grad=1e-6;
net.trainParam.max_fail=200;

[net,tr] = train(net,p,t);
y= sim(net,p);
```

**BFGS Quasi Newton**

```matlab
p=ent';
t=sal';
net = newff(p,t,15,{},'trainbfg');

net.divideParam.trainRatio = 70/100; % training
net.divideParam.valRatio = 15/100; % validation
net.divideParam.testRatio = 15/100; % test

net.trainParam.epochs=200;
net.trainParam.min_grad=1e-6;
net.trainParam.max_fail=200;

[net,tr] = train(net,p,t);
y= sim(net,p);
```
Resilient Back-propagation

\[ p = \text{ent}'; \]
\[ t = \text{sal}'; \]
\[ \text{net} = \text{newff}(p, t, 15, \{\}, '\text{trainrp}') \]

\[ \text{net.divideParam.trainRatio} = 70/100; \quad \% \text{training} \]
\[ \text{net.divideParam.valRatio} = 15/100; \quad \% \text{validation} \]
\[ \text{net.divideParam.testRatio} = 15/100; \quad \% \text{test} \]

\[ \text{net.trainParam.epochs} = 200; \]
\[ \text{net.trainParam.min_grad} = 1 \times 10^{-6}; \]
\[ \text{net.trainParam.max_fail} = 200; \]

\[ [\text{net}, \text{tr}] = \text{train}(	ext{net}, p, t); \]
\[ y = \text{sim}(	ext{net}, p); \]

Scaled Conjugated Gradient

\[ p = \text{ent}'; \]
\[ t = \text{sal}'; \]
\[ \text{net} = \text{newff}(p, t, 15, \{\}, '\text{trainscg}') \]

\[ \text{net.divideParam.trainRatio} = 70/100; \quad \% \text{training} \]
\[ \text{net.divideParam.valRatio} = 15/100; \quad \% \text{validation} \]
\[ \text{net.divideParam.testRatio} = 15/100; \quad \% \text{test} \]

\[ \text{net.trainParam.epochs} = 200; \]
\[ \text{net.trainParam.min_grad} = 1 \times 10^{-6}; \]
\[ \text{net.trainParam.max_fail} = 200; \]

\[ [\text{net}, \text{tr}] = \text{train}(	ext{net}, p, t); \]
\[ y = \text{sim}(	ext{net}, p); \]
Fletcher-reeves Conjugate Gradient

\[
p=\text{ent}';
\]
\[
t=\text{sal}';
\]
\[
\text{net} = \text{newff}(p,t,15,{},'\text{traincfg}');
\]

\[
\text{net.divideParam.trainRatio} = 70/100; \quad \% \text{ training}
\]
\[
\text{net.divideParam.valRatio} = 15/100; \quad \% \text{ validation}
\]
\[
\text{net.divideParam.testRatio} = 15/100; \quad \% \text{ test}
\]

\[
\text{net.trainParam.epochs}=200;
\]
\[
\text{net.trainParam.min\_grad}=1e-6;
\]
\[
\text{net.trainParam.max\_fail}=200;
\]

\[
[\text{net},\text{tr}] = \text{train}(%\text{net},p,t);
\]
\[
y= \text{sim}(%\text{net},p);
\]