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Structural Analysis of Internal Fixation for fractured bone using locking compression plate (LCP)

A Thesis Submitted to the Council of College of Engineering, University of Diyala in Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

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2022 August 1444 Moharam

بسم الله الرحمن الرحيم

﴿ اقْرَأْ بِاسْمِ رَبِّكَ الَّذِي خَلَقَ ﴿1﴾ خَلَقَ
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صدق الله العظيم

سورة العلق (1–5)

Dedication

To my family
and wife
To my friends
with love
and respect

Acknowledgments

At the beginning, I express my gratitude to ***Al-Mighty Allah*** who gave me the will and patience to fulfill this work, Secondly I would like deeply to thank, beloved ***MUHAMMAD*** (peace be upon him and his family). In addition, I submit the highest thankfulness, regards and respects to all those who ignited a candle to my work, and to all those who stand behind platforms to give knowledge to illuminate my way, and I extend to them all respect and regards.

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Abstract

The ability of bone to heal after the damage is both exceptional and amazing. Fractures can, however, occasionally fail to heal. Therefore, the repair of bone's structure, composition, and function is the main objective of fracture therapy. Devices for fixing fractures should create an ideal mechanical and biological environment for healing. The use of internal fixation provide less invasive method. The healing process depends on the mechanical stability of the fixation-fractured bone complex. The degree of limb loading and the fixation device stiffness have major contribution to this stability. The goal of this research is to determine the fixation steadiness of an internal plate fixation device as well as the changes impact to its configuration upon the implant steadiness. The material properties of plate and screws (Stainless Steel or Titanium), and configuration has been represented by changing the plate offset to the bone, the working length, active plate length, screw number and screw spacing (Experimentally and numerically).

In 3D stiffness the stiffness was increased when the implant material was changed from titanium to stainless steel. The direction of the moment about the (Y) axis had the most remarkable increase in stiffness (68%) by finite element analysis. In individual stiffness the stiffness was increased when the implant material was changed from titanium to stainless steel. The direction of the axial force in (Z axis) had the most remarkable increase in stiffness (60 %) by finite element analysis.

In 3D stiffness, the stiffness was decreased when the implant was offset from the bone by 1mm, and 2mm. The direction of axial force had the most significant decrease in stiffness (44%, and 50 respectively) by finite element analysis. In individual stiffness, the stiffness was decreased when the implant was offset to the bone 1mm , and 2mm. The direction of axial force had the most significant decrease in stiffness (50 , 57 % respectively) by finite element analysis. In individual stiffness, the stiffness was decreased when the implant was offset to the bone 1mm, and 2mm. The direction of axial force had the most significant decrease in stiffness (40 , 50 % respectively) by experimental analysis.

In 3D stiffness, all stiffness components were significantly decreased (≥28%) when increasing the working length and the length of plate. The direction of shear force in the (Y) axis had the most significant decrease in stiffness (57%) by finite element analysis.In individual stiffness, all stiffness components were significantly decreased (≥22%) when increasing the working length and the length of plate. The direction of axial force in the (Z) axis had the most significant decrease in stiffness (59%) by finite element analysis.In individual stiffness, all stiffness components were significantly decreased (≥3%) when increasing the working length and the length of plate. The direction of axial force in the (Z) axis had the most significant decrease in stiffness (67%) by experimental analysis.

Stiffness was increased when the implant material was changed from titanium to stainless steel. Also, all stiffness components were decreased when increasing the offset between the bone and the plate, and were decreased when increasing the working length and the length of plate.

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LIST OF ABBREVIATIONS

LCP - Locking Compression Plate

FEA - Finite Element Analysis

CT - Computed Tomography

RD - Radiographic Density

HU - Hounsfield Unit

BMD -,Bone Mineral Density

IFM - Inter-Fragmentary Movement

HHP - Hemi Helical Plate

DICOM - Digital Imaging and Communication in Medicine

STL - Stereolithography

NURBS - non-uniform rational B-spline surfaces

IGES - International Graphics Exchange Standard

3D - 3 Dimensional

AP - Anterior-Posterior

ML - Medial-Lateral

CHAPTER ONE

INTRODUCTION

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INTRODUCTION

1.1 Introduction

The present chapter starts with an introduction to the basic anatomy of bone, function of a bone, fracture of bone, types of fixation device, with the describes the plates and screws that used in internal fixation. The main functions of bone, a crucial component of the skeleton, are to support the body, safeguard the internal organs, and facilitate movement. Bone fractures when it is unable to resist the force being applied to it from outside. Bone fractures can repair on their own without the need for surgery because of the skeletal skeleton's capacity to regenerate. But occasionally they don't recover quickly enough without medical attention. Therefore, the purpose of all fracture treatments is to restore the structure, content, and form of the bone by creating the favorable mechanical and biological conditions required for quick and effective healing.

1.2 Bone

Bone is the substance that forms the skeleton of the body. In the average individual, skeletal tissue is very complex, accounting for around 14% of body weight. It is composed chiefly of calcium phosphate and calcium carbonate. It also serves as a storage area for calcium, playing a large role in calcium balance in the blood [1].

1.2.1 Function of a Bone

The 206 bones in the body serve several different purposes. They support and protect internal organs (for example, the skull protects the brain and the ribs protect the lungs) [2]. Muscles pull against bones to make the body move. Bone marrow, the soft spongy tissue in the center of many bones, makes and stores blood cells. The bone must be rigid, strong, and light in weight to fulfill its fundamental function. The architecture (form and sizes) and the bone material's mechanical properties affect its stiffness and strength. Bone strength and stiffness alter with bone mass and structure, with obvious variations during development, remain more or less stable at maturity, and degrade as people age. The mechanical loading conditions is known to affect the mass and structure of bones [3].

1.2.2 Structure of Bone

The epiphysis, metaphysis, and diaphysis are the three distinct sections that make up the long bones, as shown in Figure (1.1). A hollow medullary cavity is surrounded by a tube formed by the cortex. Spongy or cancellous bone is located towards the internal cortical surface and at the ends of the bones. The bones are covered via connective tissue as well as membranes on both the inside and outside; the periosteum covers the bone externally. The internal marrow cavities are bordered by the endosteum, whereas cartilage covers the articular surfaces. Bone-forming cells can be found in both the endosteum and the periosteum. The medullary cavity as well as inter-trabecular gaps into the cancellous bone contain a red marrow, which produces blood cells [1].

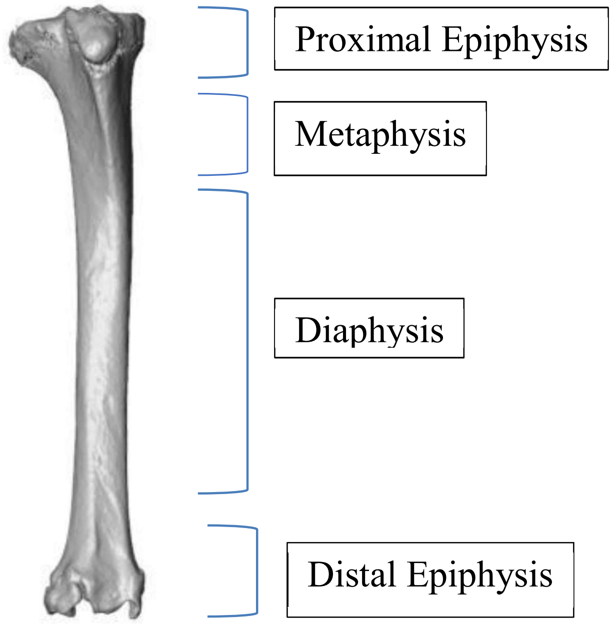

Figure (1.1) : The ovine tibia bone's surface with the illustrations of the three regions of a tibia bone from computed tomography (CT) data.

There are three basic kinds of bones: **Woven bone (callus)**: Woven bone (callus) is made up of randomly ordered collagen bundles and irregularly formed vascular gaps lined by osteoblasts. It's created during embryonic development or fracture repair [4,5]. Cortical or cancellous bone finally takes the place of woven bone [5]. Woven bone is mechanically inferior to cortical bone due to its loose nature [6].

Cortical or compact bone (Figure 1.2**):** Vascular channels that enter the embryonic bone from its periosteal as well as endosteal surfaces remodel the compact or the cortical bone, whose fundamental structural unit being an osteon. Its mechanical strength is determined by how closely osteons are packed [5]. The diaphysis long bones and the thin shells surrounding the metaphysis make up cortical bone.

Cancellous or trabecular bone (Figure 1.2**):** The trabecular or cancellous bone density is lower than that of cortical bone. Based on relative density, bone tissue is classified as cortical or trabecular. In the metaphysis and epiphysis, trabecular bone occurs as a 3D interconnected grid of trabecular plates and rods in the metaphyseal shell's internal surface [3].

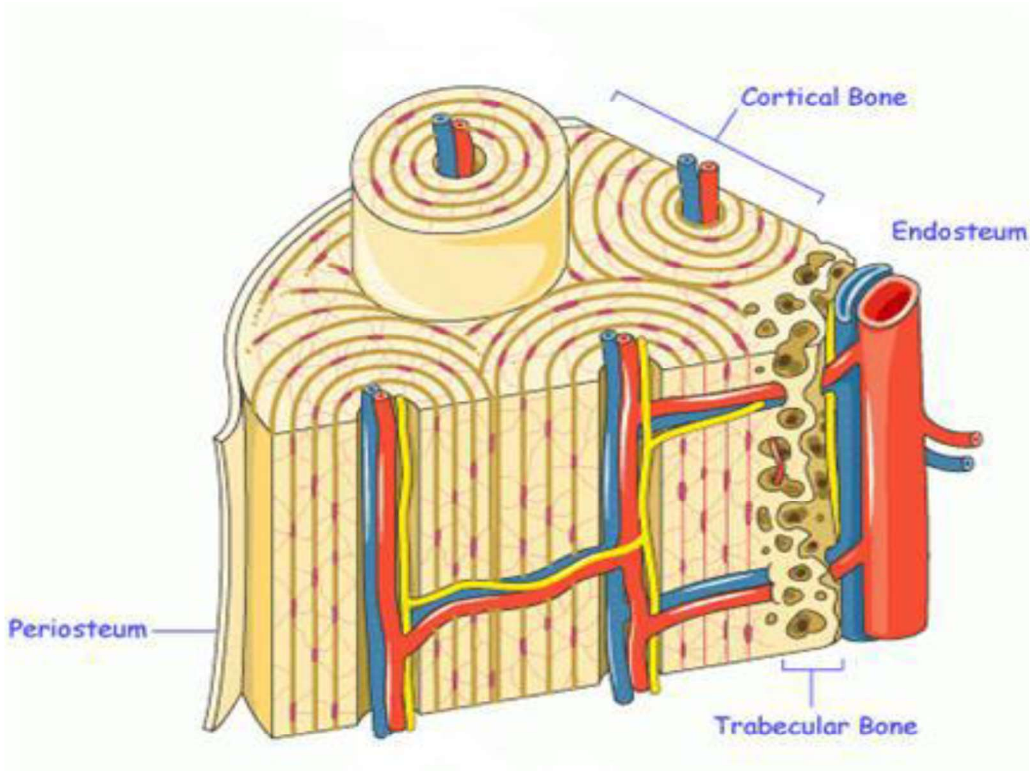

Figure (1.2): The Cross-sectional view illustrating types of bone [2].

1.3 Bone Fractures

A fracture is defined as a break in the continuity of the bone. Two types of fractures can occur in the diaphysis of long bones: undisplaced (un displaced fracture is one in which the bone cracks or breaks but retains its proper alignment) and displaced (displaced fracture is one in which the ends of the bone have come out of alignment) [7]. Transverse, oblique, spiral, comminuted, and Segmental fractures are the five displaced fractures kinds. Transverse fractures (in this study, the bone was fractured transversely) are those that occur perpendicular to the long axis of the bone and can be caused by a variety of things. A fall from a high height might cause a failure due to the bending or tensile loads, a straight hit to bone, or an obliquely transmitted force. Trauma to the bone can cause the fracture to become increasingly comminuted as the force increases [7,8]. Oblique fractures are defined by an oblique line extending 30-45 degrees from the long axis are usually caused by a combination of bending and torsional forces [7,8]. Spiral fractures are a type of broken bone. They happen when one of the bones is broken with a twisting motion. They create a fracture line that wraps around the bone and looks like a corkscrew [8,9]. A comminuted fracture is one in which there are more than two bone pieces, typically tiny wedges and no reducible fragments [8,10]. Segmental fractures are comminuted fractures in which the pieces are entire and big enough to be rebuilt anatomically [2]. These fracture Types are depicted in Figure (1.3).

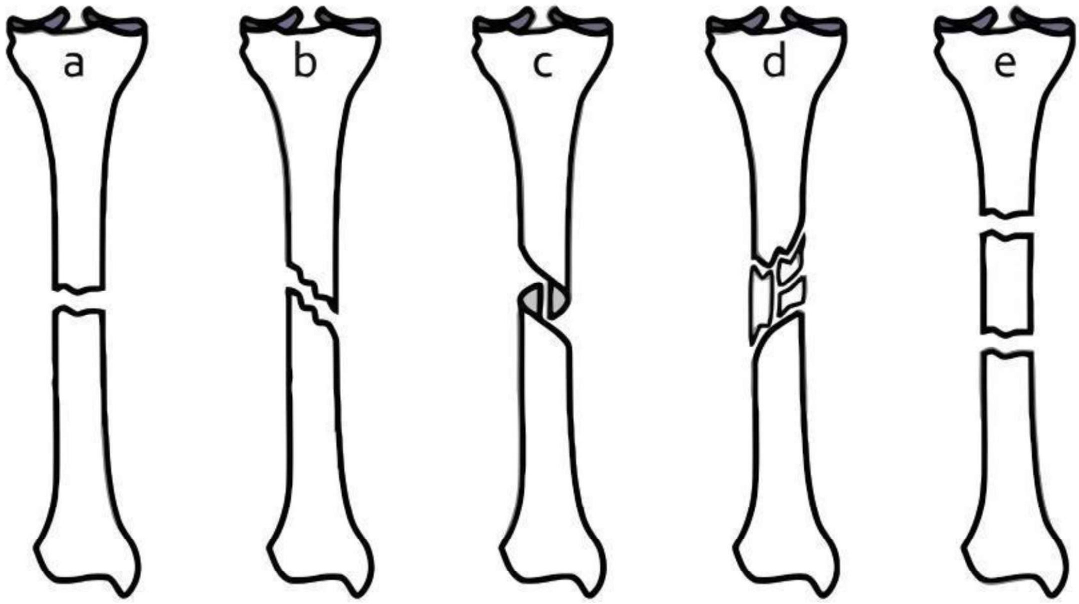

Figure (1.3) : Types of fracture: (a) transverse (b) oblique (c) spiral (d) comminuted, and (e) segmental [2].

1.4 Principles of Fracture Fixation

There're two major fracture fixation principles, and also the whole fracture fixation systems follow one of these two concepts.

1.4.1 Inter-fragmentary Compression Stabilization

The bone heals via a straight bone healing mechanism, with no or minimum callus production under totally steady circumstances [11]. If the compression throughout the entire fracture cross-section is high enough, the whole forces as well as the moments function at the location of fracture being neutralized. At these circumstances there's no inter-fragmentary shift between the two fractured pieces [3]. The lag screws, tension band regimes, and compression plates, can all help to produce this inter-fragmentary compression [12].

1.4.1.1 Compression Plate

The fixation plate is first screwed into place upon a single piece of bone. The device of tension, which moves the plate axially and is positioned on the second fragment, is then utilized to momentarily draw both fragments together, resulting in inter-fragmentary compression Figure (1.4). Later, more screws are used to secure the second component to the plate. The plates with a tapered screw hole on which the screw head glides can also be used to compress two pieces. When the screw is placed into the bone, the screw hole slope being axially pressed, causing the screw to progress towards the bone cortex. The compression created using compression plates is static, meaning it does not alter with changing weights or muscle activity (static compression) [3].

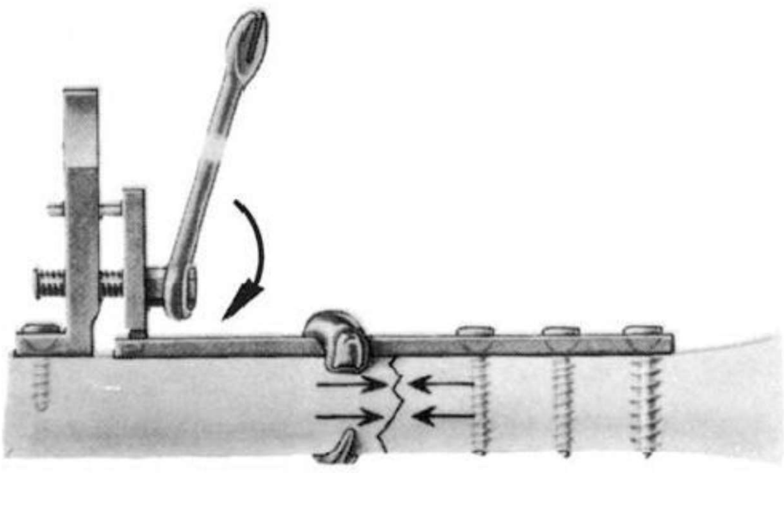

Figure (1.4) : Müller's plate tightens a tensioner that's momentarily attached to the plate and bone to induce inter-fragmentary compression [2].

1.4.2 Non-compressive Stabilization

The fracture pieces are not forced against one another by any external compressive force, as the term implies. The stabilization of fragments is achieved by attach an implant that uses screws to hold the two pieces together. A skeletal fracture heals similarly to how a wound heals in the body. Callus development mechanically joins the bone fragments during fracture healing under inter-fragmentary movement [3].

1.4.2.1 The use of bridging plates to bridge osteosynthesis

The most important rule is to avoid disturbing the fractured pieces. The soft tissue envelope is used to recreate a bone fragments cylinder, with the main, distal, and proximal segments being distracted as well as extended to length. As a result, the pieces of fracture aren't powerless nor corrected, exiting the delicate soft tissue attachments unaffected. A variety of procedures can be used to accomplish bridging osteosynthesis. Three or four screws secured distally as well as proximally in the undamaged sections of the fractured bone can be utilized for bridging two fracture fragments with a standard plate. This approach has been shown to have two advantages:

- Because the plate extends a significant distance lengthways the zone of fracture, the load upon the plate bottom that isn't fastened to bone may be dispersed above a longer space, lowering the risk of fatigue failure in particular locations.
- Because the plate is attached to the bone at a distance, it allows for a greater vascular supply [13,14].

1.5 Kinds of the Fracture Fixation Devices

There're a variety of internal and external devices available to treat fractures, which may be classified into two groups based on whether the device being incompletely in the skin for bracing reasons merely, while the main fixator part leftovers outer the surface of skin (external fixator) as shown in figure (1.5) , or completely within the skin (internal fixator) as shown in figure (1.6).

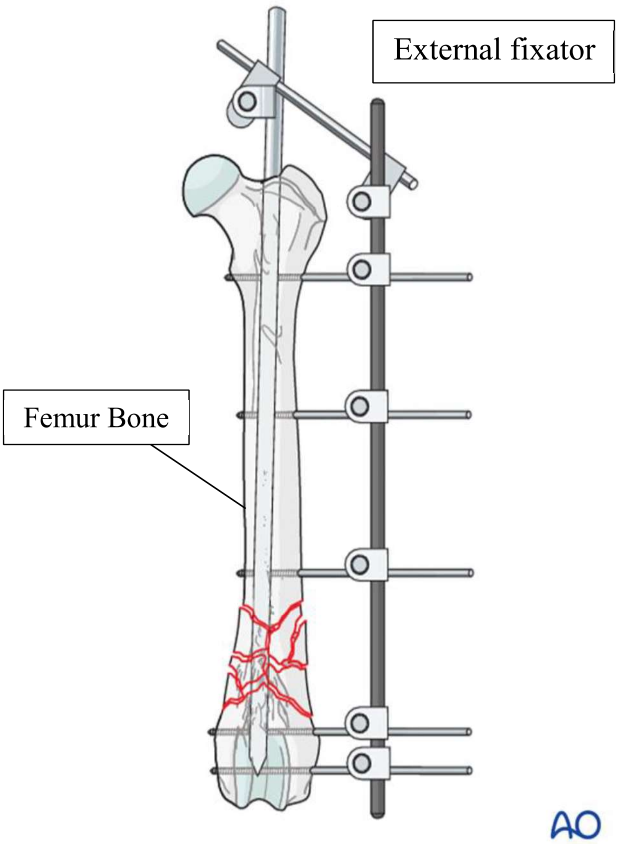

Figure (1.5) : External fixator [2].

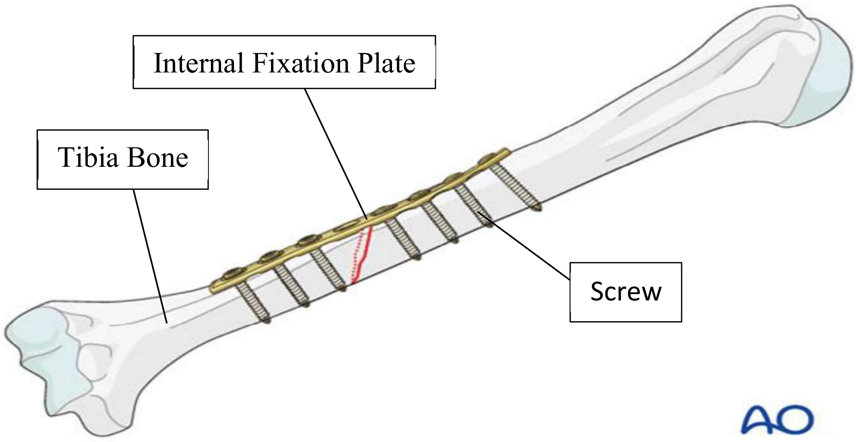

Figure (1.6) : Internal fixator [2].

1.6 Internal Fixation Plates

To keep the two bone pieces together, internal fixation plates are attached to the bone in a similar manner to an external fixator but beneath the skin [15]. Internal plate fixators, which provide lower or no plate-bone contact, are thought to minimize vascular disruption caused by implants [16]. Locking Compression Plates are one of the most frequently utilized internal plate fixation systems today. Only the internal plate attachment device will be studied in this proposed study.

1.7 Plate

Plates are made to help with one or more of the following fracture fixation functions: compression, neutralization, bridging, and buttressing. By using a tensioning mechanism or eccentrically loaded screws, compression plating creates axial forces. Simple transverse fractures and those with low obliquity are commonly treated with this technique. The system operates in a neutralization mode when a diaphyseal fracture is repaired with a plate and screws and does not create any compressive axial forces[17]. Because the plate is subjected to full weight-bearing forces, the soft tissue around the pieces must maintain its vascular supply, as indirect reduction success depends on creating the bridging callus [2].

1.7.1 Locking Compression Plate (LCP)

The locking compression plate (LCP) is a one-of-a-kind implant that combines the vascularity-preserving underlying geometric benefits of the LC-DCP system with the ability to avoid applying compressive forces to the bone. This is accomplished with locking head screws, although the LCP is a combined hole plate that also accepts regular screws [2]. The locking head screws are advantageous for angular stability and removing compressive forces from the bone fragment surfaces. One-half of each hole is designed to accommodate the standard DCP and LC-DCP screws for fragment compression, while the other half is designed to accommodate the locking head screws for angular stability and removal of compressive forces from the bone fragment surfaces. Because locking head screws have a greater core diameter, they strength bending and shear strength while distributing the stress over a broader region of the bone. Because of the angular stability provided by locking head screws, the importance of correctly contouring the plate is reduced [2]. Figure (1.7) is a representation of this plate.

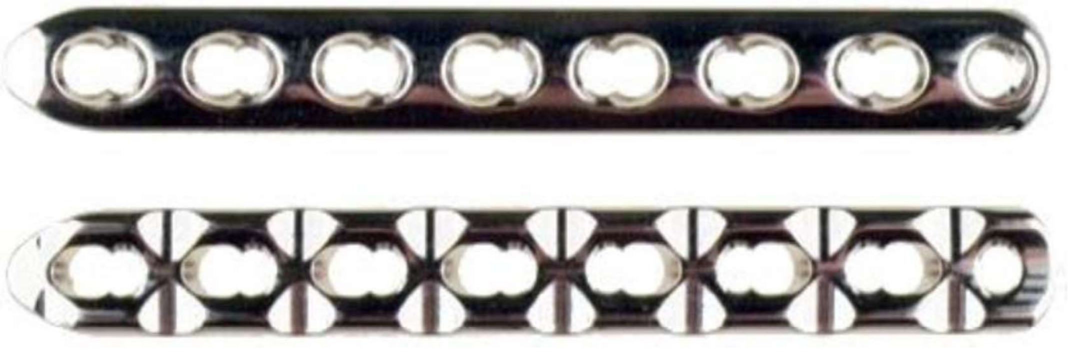

Figure (1.7) : Locking Compression Plate(LCP).

1.8 Screws

To avoid a reduction in bone strength, the doctors should use screws that are no more than 40% of the diameter of the fracture bone [2]. Depending on the plate being fitted, conventional or locking head screws can be used for implantation. Both cancellous and cortical bone can be accommodated with standard screws. Cortical screws have a thicker inner core with shallower threads than cancellous screws, which have a thin core with wide and deep threads. The cancellous screws have a substantially higher holding ability in the trabecular bone of the metaphases and epiphyses due to the increased ratio of the outer diameter to the inner core. In diaphyses, cortical screws are commonly employed. When used to attach plates to bone, they can be entirely or partially between bone fragments, depending on whether lag screws are employed [2].

1.8.1 Standard Screws

Standard screws are used in normal plates when it is expected that the screw will need to be replaced or repositioned throughout the healing process. After drilling a pilot hole in the bone, threads are cut into the hole using a tap that matches the threads on the screw being used. Standard screws may be easily withdrawn and reinserted without the risk of thread damage [2]. Figure (1.8) shows a conventional screw.

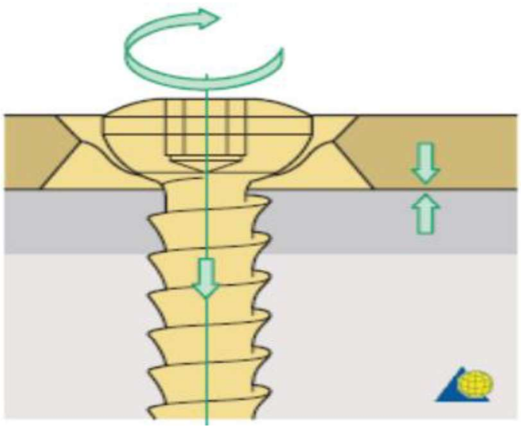

Figure (1.8) : Conventional Screw [2].

1.8.2 Locking Head Screws

In addition to threads encircling the head of the screw, locking head screws may contain conventional or self-tapping threads on their core. The screw head fits into the plate hole, which is threaded to fit them. The threads on the head are of a different pitch and diameter than those on the core, resulting in increased pullout resistance and the capacity to eliminate any compressive forces between the plate and the bone. This is critical in preventing vascular disturbance surrounding the damaged area. Additionally, because plates are sometimes curved and tilted to better fit their application, these screws ensure that the plate's placement is not disrupted [2]. Figure (1.9) shows a locking head screw.

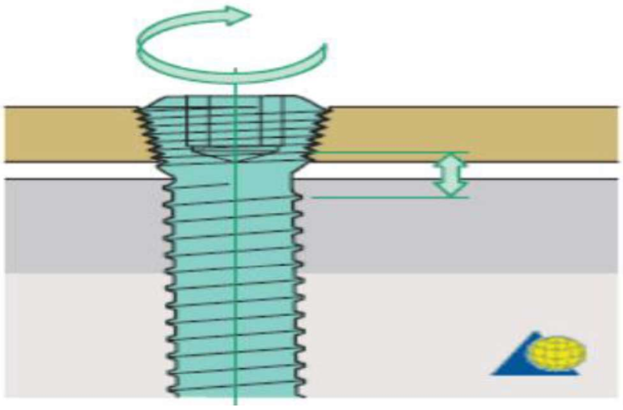

Figure (1.9) : Locking head screw [2].

1.9 Finite Element Analysis (FEA)

A numerical tool for solving complicated engineering issues is the finite element method. When faced with a complicated engineering challenge, it is frequently helpful to describe the intricate regimes in relating an easy regime or a system model via separating the key features. Then, such model may be utilized for tracking the behavior of system in reaction to changing input factors or circumstances. Physical modeling, in which real structures are produced, or mathematical modeling, in which conceptual representations are used, are two types of modeling. Finite element (FE) models are numerical mathematical models that rely on computers to discover approximate answers [18]. The supplementing of structurally as well as mathematically specified FEs, coupled collected via generally shared nodes, can be used to construct a system. When a load is applied to a system, the localized response of each element is calculated to solve the state of the load of system, indicating the reason and effective link between the loads positioned upon the system, as well as the mechanical behavior it produces, such as stresses and strains. The real mechanical environment created in a bone via the fixator use can be quantified and comprehended using this method in an orthopedic setting. The FE approach is employed in orthopedic research in a variety of domains, including device analysis and design, tissue growth and remodeling analysis, and more skeletal deterioration and examination. In 1972, FEM was used for the first time in orthopedics [18,19]. Following that, with the rapid advancement of procedures and complexities in recent years, its usage in orthopedic research has increased. One of the most significant benefits of adopting FE is that it eliminates the problems of variability and repeatability that plague experimentation. Any model, on the other hand, is an attempt to represent reality. Because not all the factors regulating the process can be included during such a representation, a model is only a simplification of the complicated actuality. Owing to the numerous suppositions as well as explanations that go into a FE model production, an investigational method (physical model, such as mechanical testing) must come before FEA for validating the model.

1.10 Bones Computed Tomography (CT)

CT pictures, such as the X-Ray images, indicate an object's radiographic density (RD), which is the relative attenuation of x-rays by the tissue rather than its true density. In computed tomography, a computer stores the X-Ray data attenuation as well as creates a pixel matrix. Each pixel's x-ray data attenuation is characterized by a gray shade, which being given a computed tomography number. in Hounsfield Units (HU). As a result, the observed picture of computed tomography is made up of a pixels matrix. Because CT pictures are tomographic, each pixel represents a tiny amount of tissue (3D), called a voxel. Converting intensity data (HU) to bone mineral density (BMD) is possible by computed tomography scanning a thing of concern (bone) along a thing of the recognized density of a comparable substance (bone phantom). The bone model geometry being most typically determined from the bone's computed tomography scans at tissue. Such method produces a highly accurate three-dimensional model and has been used to make human bone models [20,21,22,23,24]. Computed tomography (CT) technology is also used to measure bone density.

1.11 Animal (Ovine) Models in Orthopedic Research

These models, like the ovine model, are frequently used in the investigational orthopedic study [25]. Structure of a hind leg of sheep is quite similar to that for human, with a femur as well as tibia that are just somewhat shorter than the normal bones of human. Furthermore, information from the human volunteers or the cadaveric bones isn't continuously freely obtainable. As a result, the femoral as well as tibia implants may be tried upon them (sheep) having modest size changes. Researchers can collect additional information on healing processes using these mimics. Furthermore, animal model trials are an important aspect of pre-clinical testing.

1.12 Problem Description

For fracture therapy, there are numerous different types of fixation devices. The fixation stability is recognized to possess an impact upon the healing results. The technology of internal fixation has increasing popularity over external fixation. Internal fixation is designed to offer enough stability for healing while still allowing for some inter-fragmentary mobility (flexible fixation), which promotes the callus development. [26,27,28].

The stiffness of the fixation device is used to determine fixation stability. A good fixation stiffness estimation approach is required for investigating the internal fixator arrangement impact upon the implant steadiness and finally, the stability. There have been several stiffness determination methods described, all of which vary in the way as well as the orientation in which the loads being exerted, in addition to the way the displacements being recorded [29,30,31].

Because there is no common approach to assess the fixation stability, selecting a method for characterization of internal fixation devices is difficult.

1.13 Thesis Objectives

The main objective of current research is to conduct numerical and experimental analysis to investigate the effect of number of parameters that influence the bone fixation stability. The investigated parameters include:

i. Plate and screws' material properties will be simulated as stainless steel or titanium.
ii. Plate offset (distance from the underside of the fixator to the bone surface).
iii. Working length (the distance between the proximal and distal screw in closest proximity to the fracture).
iv. Effective plate length (effective plate length of 6-hole with three screws on either side of the fracture gap).
v. Screw spacing.
vi. Screw number.

1.14 Thesis Layout

Chapter One includes:

- Introduction to topic (anatomy and functions of the bones, types of bone fractures and principles of fracture fixation including kinds of fracture devices , types of plates and screws used for fixation of the long bones)
- Definitions related to finite element method
- Problem description and
- Objective of the research.

Chapter Two includes:

- Review of the published literatures on the effect of configuration (material properties, including the geometry of the fixator, the number, and the location of the screw; the type of screw; the arrangement of the screw, and an offset spacing from the fixator to the bone; their effect on the fixator stiffness.
- Methods of calculating the stiffness (both 3D and individual stiffness)
- Boundary conditions effecting the inter-fragmentary movement at the fracture gap.
- Reviewing literatures that compare between experimental an finite element method.

Chapter Three include:

- Creating a 3D bone model from a computed tomography (CT) image of a ovine tibia bone, and modeling implant-bone constructions by ANSYS Workbench.
- How to calculate the stiffness for implant bone construction

Chapter Four : illustrates the experimental work concerning six load cases to find individual stiffness components for load cases.

Chapter Five : comprises the experimental and theoretical outcomes and their debate.

Chapter Six : Conclusions of the research