The effect of the increased posterior tibial slope on the integrity of the anterior cruciate ligament and patterns of the meniscal injury: a methodological approach

Ashraf Elmansori

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THESE de DOCTORAT DE L'UNIVERSITE DE LYON

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(Mécanique Energétique Génie civil et Acoustique)

Spécialité de doctorat : Biomécanique

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ASHRAF EL MANSORI

Titre de la thèse

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Devant le jury composé de :

CHEZE Laurence	Professeur	Université Lyon 1	Présidente
DESCAMPS Stephane	Professeur	CHU de Clermont Ferrand	Examinateur
HAGEMEISTER Nicola	Professeur	Ecole de Technologie Supérieure	Examinatrice
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SUMMARY

The aim of this work was to report a comprehensive literature review comparing the different methods and techniques of measurement of the posterior tibial slope (PTS) among the conventional radiograph, Computed tomography (CT), and magnetic resonance imaging (MRI) in order to help the orthopedic surgeons to establish a standard and reliable measurement method. The work also includes two retrospective studies measuring the tibial slope using different modalities.

It has been reported that the PTS has an influence on the on the kinematics of the knee notably the anterior cruciate ligament (ACL). A better understanding of the significance of the PTS could improve the development of ACL injury screening and prevention programmes, and might serve as a basis for individual adapted rehabilitation programmes after ACL reconstruction.
Additionally, in several orthopedic interventions such as high tibial osteotomy, the tibial slope can result in altered knee mechanics. Therefore, an exact preoperative measurement of the posterior tibial slope is mandatory. Several methods are used on conventional radiographs, CT and MRI, but until now there is no standard validated method.

The first part of this work was a general introduction about the anatomical structures of interest involved in this study, namely the knee joint, the anterior cruciate ligaments, the menisci, and the tibia, this introduction part included the gross anatomy, the microscopic structure, function, and some clinical considerations.

The second part of the work is dedicated to a systematic review of the available modalities and techniques in the literature. Information regarding methods of measurement of the tibial slope in normal and ACL-injury subjects was extracted from all the studies in a systematic fashion and classified according to the measurement technique and used modalities. The most common used axis was the proximal tibial anatomical axis (PTAA), and the midpoint method is the most frequently used method for calculating the PTAA. By direct comparison, the greatest value of the medial tibial slope (MTS) for the pathological knee was achieved by the radiological studies, while the MRI studies presented the smallest values. Consequently, for the pathological lateral tibial slope (LTS), the MRI values were smaller than that of the CT studies. The greatest values of the MTS and LTS were obtained by the anterior tibial cortex axis, while the minimum values were achieved by the tibial diaphyseal axis.

This third part of the work was a case-control study, by using MRI, the LTS, MTS, lateral and medial meniscal slopes (LMS, MMS) were compared in 100 patients with isolated ACL injury and a control group of 100 patients with patello-femoral pain and an intact ACL. The most important finding of this study is that the increased tibial slopes, both bony and meniscal, are risk factors for ACL injury. As the meniscus tends to correct the observed slope towards the horizontal, loss of the posterior meniscus may potentiate this effect by increasing the functional slope.

The fourth part of the work is aimed to evaluate the effects of the patient characteristics, time from injury (TFI), and posterior tibial slope (PTS) on meniscal tear patterns. In the 362 ACL-injured analyzed patients, The most common tear location was the posterior horn (PH) of the medial meniscus (MM), followed by tear involving the whole MM. Patient age, BMI, and TFI were significantly associated with the incidence of MM tear. An increase in the tibial slope, especially of the lateral plateau, seems to increase the risk of tear of the lateral meniscus (LM), and of both menisci.

Keywords: Knee, Posterior Tibial slope, Radiography, MRI, CT scan, ACL injury, Meniscus tear, Time from injury.

RÉSUMÉ

Le but de ce travail était de rapporter une revue compréhensive de littérature comparant les méthodes différentes et les techniques de mesure de la pente tibiale parmi la radiographie conventionnelle, CT des feuilletages et MRI pour aider les chirurgiens orthopédistes à établir une méthode de mesure standard et fiable. Le travail inclut aussi deux études rétrospectives mesurant la pente tibiale en utilisant de modalités différentes.

Il a été rapporté que la pente tibiale postérieure (PTS) a une influence sur la cinématique du genou notamment le ligament croisé antérieur (LCA), une meilleure compréhension de la signification de PTS pourrait améliorer le développement du dépistage des lésions du LCA et des programmes de prévention et pourrait servir d'une base pour des programmes de réadaptation individuels adaptés après ACL la reconstruction.

De plus, dans plusieurs interventions orthopédiques comme l'ostéotomie tibiale haute, la pente tibiale peut modifier la mécanique de genou. Dès lors, une mesure préopératoire exacte de la pente tibiale postérieure est obligatoire. Plusieurs méthodes sont utilisées sur des radiographies conventionnelles, des scanners et IRM, mais jusqu'à présent il n'y a aucune méthode standard validée.

La première partie de ce travail était une introduction générale des structures anatomiques d'intérêt impliquées dans cette étude, à savoir l'articulation du genou, des ligaments croisés antérieurs, les ménisques et le tibia, cette partie d'introduction a inclus l'anatomie brute, la structure microscopique, la fonction et quelques considérations cliniques.

La deuxième partie du travail est consacrée à une revue systématique des modalités et techniques disponibles dans la littérature. Les informations quant aux méthodes de mesure de la pente tibiale chez des sujets normaux et LCA-blessés ont été extraites de toutes les études incluses de manière systématique, et ont classifiées selon la technique de mesure et les modalités utilisées.

L'axe le plus utilisé était l'axe tibial anatomique proximal (PTAA), et la méthode (Midpoint) est la plus fréquemment utilisée pour calculer le PTAA. Les valeurs les plus grandes du MTS et de LTS ont été obtenues par l'axe de cortex tibial antérieur, tandis que les valeurs minimales ont été réalisées par l'axe tibial diaphysaire.

Par comparaison directe, la plus grande valeur de la pente tibial Interne (MTS) pour le genou pathologique a été réalisée par les études radiologiques, tandis que les études de MRI ont présenté les plus petites valeurs. Par conséquent, pour la pente tibial latérale (LTS), les valeurs de MRI étaient plus petites que celui des études de CT.

La troisième partie du travail était une étude de cas-contrôle, en utilisant MRI, les LTS, MTS et les pentes de ménisque interne et externe (LMS, MM) ont été comparés dans 100 patients avec un LCA-blessé isolée et un groupe témoin de 100 patients avec une douleur patello-fémorale et LCA intact. La découverte la plus importante de cette étude consiste en ce que les pentes tibiales augmentées, tant osseux que les ménisques, sont des facteurs de risque pour la blessure LCA. Comme le ménisque a tendance à corriger la pente observée vers l'horizontale, la perte du ménisque postérieur peut potentialiser cet effet en augmentant la pente fonctionnelle.

La quatrième partie du travail est visée à évaluer les effets des caractéristiques patientes, le temps de la blessure (TFI) et la pente tibiale postérieure sur des modèles de larme de ménisque. Dans les 362 patients avec LCA-blessés, l'emplacement de la lésion méniscale le plus commun était la corne postérieur (PH) de MM, suivi par la larme impliquant le MM entier. L'âge du patient, BMI et TFI ont été significativement associés à l'incidence de lésion de MM. Une augmentation de la pente tibiale, particulièrement du plateau latéral, semble augmenter le risque de la lésion du LM et des deux ménisques.

Les mots-clés: La pente tibiale, Radiographie, IRM, Scanner, Blessures du LCA, lésion du ménisque, Le temps depuis blessure.

"Il n'existe qu'un seul moyen : plongez en vous-même, recherchez la raison qui vous enjoint d'écrire ; examinez si cette raison étend ses racines jusqu'aux plus extrêmes profondeurs de votre cœur ; répondez franchement à la question de savoir si vous seriez condamné à mourir au cas où il vous serait refusé d'écrire. Avant toute chose, demandez-vous, à l'heure la plus tranquille de votre nuit: est-il nécessaire que j'écrive ? Creusez en vous-même en quête d'une réponse profonde. Et si elle devait être positive, si vous étiez forcé à répondre à cette question grave par un puissant "je ne peux pas faire autrement", construisez alors votre existence en fonction de cette nécessité ; jusque dans ses moindres instants les plus insignifiants, votre vie doit être le signe et le témoin de cette impulsion."

Rainer Maria Rilke, Lettres à un jeune poète (1903-1908).

DEDICATION

I am dedicating this thesis to my beloved **Dad** and my sister who have meant and continue to mean so much to me. Although they are no longer of this world, their memories continue to regulate my life. First and foremost, to my Dad "**Mohamed**" whose love for me knew no bounds and, who taught me the value of hard work. Thank you so much, daddy, you will be always in my heart.

Next, my lovely sister "**Hania**" who raised me, loved me, and she was always thinking all that I do is the best, unfortunately, I can never show you my success but you will rest forever inside me.

May you all find peace and happiness in Paradise!

You have gone away forever from our loving eyes and who left a void never to be filled in our lives, but I will make sure your memory lives on as long as I shall live. I love you all and miss you all beyond words. May Allah (SWT) grant you.

Amen.

Ashraf

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To **the staff** at **the faculty of medicine at the university of Lyon 1**, I am grateful for the chance to be a part of it all. Thank you for welcoming me as a friend and helping to develop the ideas in this thesis.

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I would not have contemplated this road if not for **my family,** my Mom, my brothers and my sisters who instilled within me a love of creative pursuits, science, and language, all of which finds a place in this thesis. My parents provided me with a loving home, one where an academic mind was celebrated. To my family, I love you.

Most of all I owe my loving thanks to **Sharifa** my loving, supportive, encouraging, and patient wife whose faithful support during the stages of this PhD. is so appreciated. I appreciate your patience, resistance, and strong personality.

Thank you, to my daughter **Jana** and my sons **Abdrahim** and **Mohamed** you are my dearest treasure; you have lost a lot due to my research abroad. Without your encouragement and understanding, it would have been impossible for me to finish this work.

May the Almighty God richly bless all of you.

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Chapter 1

GENERAL INTRODUCTION

Anatomical background of the knee joint and the relative structures.

RÉSUMÉ

Le genou est la plus grande articulation dans le corps. C'est un joint composé synovial qui consiste en articulation fémoro-tibiale et l'articulation fémoro-patellaire. La fonction anatomique et la stabilité du genou dépendent des muscles, des os, des ligaments, le cartilage, le tissu synovial, le liquide synovial et d'autres tissus conjonctifs. Les 4 ligaments principaux de stabilisation du genou sont le ligament croisé antérieur (LCA), le croisé postérieur, ligaments collatéraux internes et externes.

Le genou est une articulation portant-poids qu'Il sert principalement d'une diarthrose autour d'un axe transversal dans un plan sagittal qui permet la flexion et l'extension. Pendant ce mouvement, les condyles tibiaux articulent avec condyles fémoraux aussi bien que les ménisques interne et externe. Aussi, la rotule articule avec la cannelure trochléaire fémorale.
Le genou tient secondairement compte de la rotation interne et externe, la compression et la distraction, la traduction antérieure et postérieure, la traduction interne et externe. Bien que le genou soit fondamentalement instable, il a un certain nombre de stabilisatrices dynamiques et statiques.

LCA est une structure clé dans l'articulation du genou, comme il résiste à la traduction tibiale antérieure et la rotation. C'est une des structures le plus fréquemment blessées pendant le haut impact ou des activités sportives. Donc, une compréhension adéquate de l'anatomie complexe, la fonction, la biomécanique de LCA aussi bien que les facteurs de risque possibles de blessure sont critiques d'élucider les mécanismes de blessure, comprendre le destin de manque chronique de LCA et améliorer la reconstruction.

LCA est une structure semblable à la bande de tissu conjonctif dense. Son attachement fémoral montre un modèle de demi-cercle verticalement disposé. L'attachement osseux est localisé à la partie postérieure de condyle fémoral latéral. De son attachement fémoral, LCA court antérieurement, intérieurement et distalement vers le tibia.

La forme croisée de LCA est irrégulière et change avec l'angle de flexion, il augmente du fémur au tibia. Ils attachent à un fossa situé antérieur et latéral à l'épine tibiale interne.

Fonctionnellement, LCA est divisé dans deux parties, les faisceaux antéromédial et postérolatéral, les deux faisceaux éprouvent des modèles différents de changements de longueur pendant la flexion de genou.
L'organisation complexe, ultra-structurelle, l'orientation variable des faisceaux dans le LCA et le système élastique abondant le rend très différent d'autres ligaments. LCA est une structure unique et complexe capable de résister aux tensions multiaxiales et le changement de tensions extensibles. Cette spécificité et complexité peuvent expliquer la difficulté de reproduire le ligament d'origine après la reconstruction chirurgicale.

LCA est le ligament le plus généralement blessé et la plupart du temps sans cause extérieure. Le mécanisme de blessure implique souvent un athlète qui change soudain la direction pendant la course ou le saut.
Dans la jeune population, la blessure au LCA est couramment réparée par une intervention chirurgicale pour maintenir la stabilité en participant dans des activités sportives. Une telle reconstruction vise à reconstituer la cinématique et la stabilité du genou blessé, empêcher des changements dégénératifs futurs.

L'articulation du genou contient des ménisques interne et externe placé entre condyles fémoraux correspondants et le plateau tibial. Chacun est un composant critique brillant blanc d'une articulation du genou saine. Les ligaments principaux de stabilisation sont le ligament collatéral interne, le ligament transversal, les ligaments méniscofémorals.
Bien que les ménisques sont grossièrement de forme semi-lunaire, le ménisque externe montre une plus grande variété dans la taille, la forme, l'épaisseur et la mobilité que le ménisque interne. Le ménisque externe couvre aussi une plus grande partie du plateau tibial en comparaison du ménisque interne.

Le ménisque résiste à beaucoup de forces différentes comme force de cisaillement, la tension et la compression. Il joue aussi un rôle crucial dans porteur, la transmission de charge, l'absorption de choc, aussi bien que la lubrification et la nutrition du cartilage articulaire.

La déchirure du ménisque est une autre blessure de genou très commune qui a fréquemment le même mécanisme de blessure au LCA, un mouvement pivotant sur un pied planté. Elle peut aussi arriver dans des patients plus vieux en conséquence des changements dégénératifs.

Le tibia est un os du membre inférieur, et plus exactement le plus grand des deux os de la jambe, en situation médiale et antérieure par rapport à la fibula. C'est le deuxième os par ordre de grandeur du corps humain.

L'épiphyse proximale est volumineuse et allongée transversalement. Elle est constituée de deux condyles, un latéral et un médial. Le condyle latéral est large et convexe vers le haut alors que le condyle médial est étroit et concave. Les condyles forment une surface plate, connue comme le plateau tibial.

La pente de plateau tibial n'est pas statique et change de la naissance jusqu'à la maturité squelettique. À la naissance, la pente tibiale est environ 25˚, mais des diminutions jusqu'à ce que la croissance squelettique soit complétée. À la maturité, le plateau tibial incline de 0° à 20° et la valeur absolue dépend du groupe de populations.

FIGURES

CONTENTS

1.1. KNEE JOINT

The knee is the largest joint in the body. It is a compound synovial joint that consists of the tibiofemoral joint and the patellofemoral joint.

The anatomical function and stability of the knee depending on muscles, bones, ligaments, cartilage, synovial tissue, synovial fluid, and other connective tissues (**Fig. 1.1**).

The 4 main stabilizing ligaments of the knee are the anterior cruciate (ACL), posterior cruciate, medial collateral, and lateral collateral ligaments.

The knee's bony structures include the distal end of the femur, proximal end of the tibia, and patella. The patella is the largest sesamoid bone in the body and functions as an attachment point for the quadriceps tendon and patellar ligament. The knee contains multiple bursas which serve to reduce friction between structures of the knee. Bursas are small sacs made up of synovial membranes and contain synovial fluid. Synovial fluid is made by synovial membranes and serves to reduce friction between the articular surfaces of the knee [28].

1.1.1. Function

The knee is a weight-bearing joint that It primarily serves as a hinge joint around a transverse axis in a sagittal plane which allows flexion and extension. During this motion, the tibial condyles articulate with the femoral condyles as well as the medial and lateral menisci. Also, the patella articulates with the femoral trochlear groove.

The knee secondarily allows for internal and external rotations, compression and distraction, anterior and posterior translations, medial and lateral translations. Although the knee is an inherently unstable joint, it has a number of dynamic and static stabilizers [28].

1.1.2. Embryology

In the second week of development, the structures which make up the knee begin to develop from mesoderm. Around the sixth week of development, chondrocytes have developed the cartilage form of the femur and tibia. Primary ossification centers are present in all long bones by twelve weeks of development. The ligaments, menisci, and other connective tissue develop from mesenchyme and become distinct from one another by week ten of development. The muscles and neurovascular components which contribute to the knee begin to develop from mesoderm around the fourth week [28].

1.1.3. Blood Supply and Lymphatics

The structures of the knee receive much of their blood supply from an arterial plexus from the popliteal artery and femoral artery. The popliteal artery branches off the superficial femoral artery and runs posteriorly across the knee joint. The superior medial, inferior medial, superior lateral, and inferior lateral genicular arteries branch off the popliteal artery and travel anteriorly to anastomose with other parts of the plexus. Also, a descending genicular artery branches off the superficial femoral artery and anastomoses anteriorly with the other genicular arteries. The anterior and posterior tibial recurrent arteries travel laterally from the anterior tibial artery and to contribute into the plexus. The middle genicular artery travels directly into the joint. In addition, the sural arteries branch off the popliteal artery and travel inferiorly away from the midline [28].

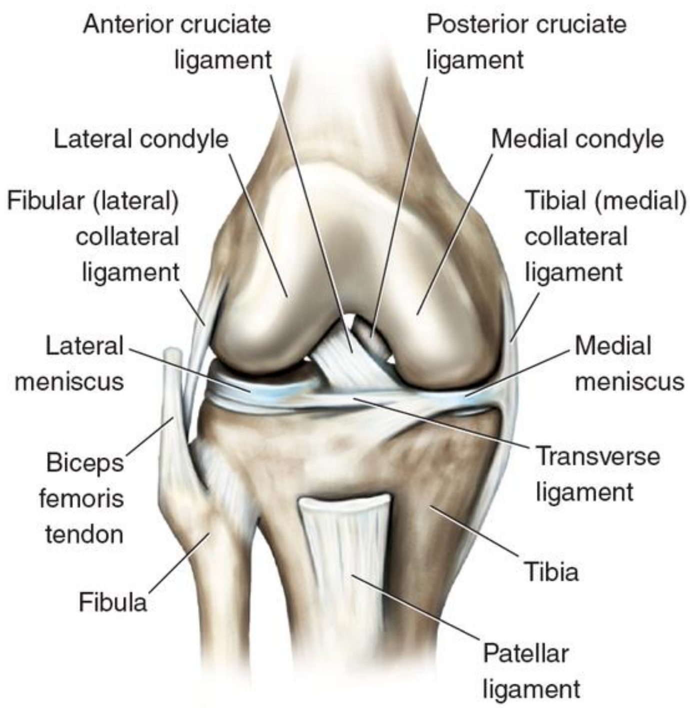

Fig.1.1: Anatomy of the knee joint and its ligaments.

Much of the lymphatic drainage from the knee and lower leg travel to the popliteal lymph nodes, which are located in the popliteal fossa. The popliteal nodes along with other knee and lower limb lymphatics drain into the deep inguinal and sub inguinal nodes. The lymphatic system primarily follows vasculature.

1.1.4. Nerves

The structures of the knee and most of the flexor muscles receive innervation from branches of the femoral nerve (L1, L2, L3). The extensor muscles receive innervation from the sciatic nerve (L4, L5, S1, S2, S3) which branches into the tibial nerve and common peroneal nerve [28].

1.1.5. Muscles

Flexion is predominately accomplished by the articularis genus, rectus femoris, vastus lateralis, vastus intermedius, and vastus medialis. These muscles originate from various locations on the femur and anterior inferior iliac spine. The latter 4 conjoin to form the patellar tendon, which crosses the knee anteriorly and inserts on the patella and tibial tuberosity.

The extension is predominately accomplished by the biceps femoris, semitendinosus, semimembranosus, gastrocnemius, plantaris, gracilis, and popliteus. These muscles originate from the ischial tuberosity, inferior pubic ramus, and different locations on the femur. They insert in various locations of the tibia, fibula, and calcaneus [28].

1.1.6. Surgical Considerations

Ligaments and meniscal tears are among the most common knee injuries and typically require surgical intervention. Often, ligament repairs are done arthroscopically, with a number of different grafts such as hamstring, patellar, and allograft being used to repair the defect. Ligaments repairs commonly require extensive rehabilitation and athletes routinely wear a brace during an activity to prevent recurrence. Arthroscopy is also used to repair meniscal tears, or more commonly to perform a meniscectomy on the damaged meniscus. Meniscectomy is a faster recovery but still requires some rehabilitation. One of the main functions of ligamentous structures and menisci are to provide stability to the joint. When these structures become compromised, the articular surfaces of the knee can be more prone to sustain damage that may lead to osteoarthritis. Ultimately, this osteoarthritis can cause great pain and discomfort with a significant decrease in functionality and quality of life. A total knee arthroplasty (TKA) can be performed to treat this condition. This type of surgery is more prevalent in the older population and requires extensive rehabilitation as well [12, 16, 19].

1.2. ANTERIOR CRUCIATE LIGAMENT

The ACL is a key structure in the knee joint, as it resists anterior tibial translation and rotation. It is one of the most frequently injured structures during high impact or sporting activities [26]. Therefore, an adequate understanding of the complex anatomy, function, biomechanics of the ACL as well as the possible risk factors of injury is critical to elucidate the mechanisms of injury, understand the fate of chronic ACL deficiency, and to improve the reconstruction.

1.2.1. Embryology

The ACL appears as a mesenchymal condensation in the blastoma at 6 weeks of gestation before joint cavitation. It is surrounded by a mesentery-like fold of synovium that originates from the posterior capsular apparatus of the knee joint. Thus, while the ACL is located intraarticularly, it remains extra-synovial throughout its course [9].

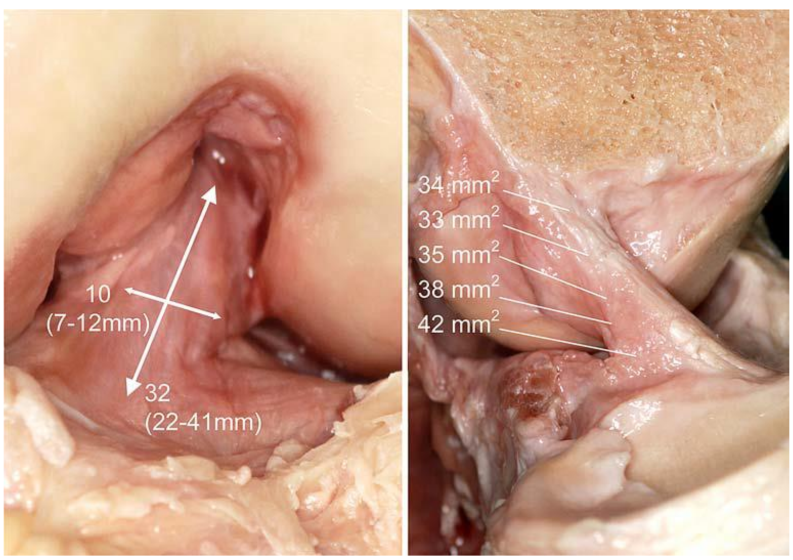

Fig. 1.2: Front view of a left knee showing the ACL in the femoral intercondylar notch. The mean length is 32 mm (left) and the mean width is 10. The cross-sectional area varies in size and shape from the femur to the tibia (right) [8].

1.2.2. Gross Anatomy

The ACL is a band-like structure of dense connective tissues. Its femoral attachment displays a vertically disposed semi-circle pattern. The bony attachment is located at the posterior part of the inner surface of the lateral femoral condyle. The ACL is lateral to the midline and occupies the superior 60% of the lateral aspect of the femoral notch. From its femoral attachment, the ACL runs anteriorly, medially, and distally to the tibia. Its length ranges from 22 to 41 mm and its width from 7 to 12 mm [2] **(Fig. 1.2).**

The cross-sectional shape of the ACL is irregular and changes with the angle of flexion, it increases from the femur to the tibia.

The ACL fibers fan out as they approach their tibial attachment. They attach to a fossa located anterior and lateral to the medial tibial spine. Near its attachment, the ACL sends fibers anteriorly beneath the transverse inter-meniscal ligament and may blend with both the attachment of the anterior or posterior horn of the lateral meniscus. The tibial attachment is somewhat wider and stronger than the femoral attachment [2, 28].

Functionally, Girgis et al. divided the ACL into two parts, the anteromedial bundle (AMB) and the posterolateral bundle (PLB) [11] (**Fig. 1.3**).

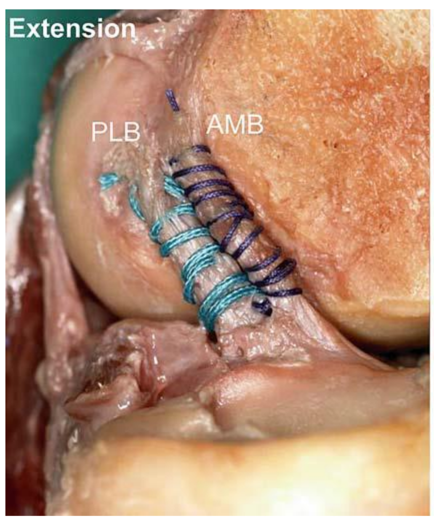

Fig. 1.3: The AMB and the PLB of the ACL [8].

The fascicles of the AMB originate at the most anterior and the proximal aspect of the femoral attachment and insert at the anteromedial aspect of the tibial attachment. Conversely, the fascicles of the PLB originate at the postero-distal aspect of the femoral attachment and insert at the posterolateral aspect of the tibial attachment. A larger number of fascicles make up the PLB as compared to the AMB. The two bundles experience different patterns of length changes during knee flexion [2, 11].

1.2.3. Histology

Microscopically, we can distinguish three zones within the ACL:

1. The proximal part, which is less solid, is highly cellular, rich in round and ovoid cells, collagen type II and glycoproteins such as fibronectin and laminin **(Fig. 1.4a)**.

2. The middle part, containing fusiform and spindle-shaped fibroblasts, is a high density of collagen fibers, a special zone of cartilage and fibrocartilage, and elastic, and oxytalan fibers. The oxytalan fibers withstand modest multidirectional stresses, while elastic fibers absorb recurrent maximal stress. The cytoplasm of the cells in this zone appears to be intimately attached to the extracellular collagen and follows the crimp waveform of the fibers (**Fig. 1.4b**).

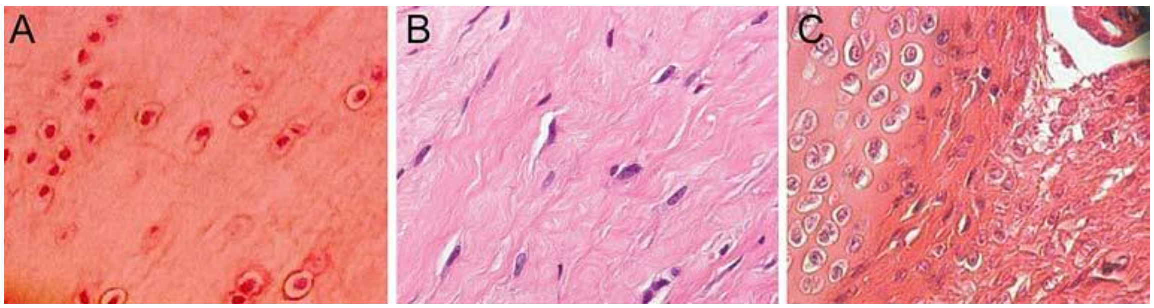

Fig. 1.4: The three histological zones of the ACL. The proximal part which is highly cellular with round and ovoid cells (a), the middle part with fusiform and spindle-shaped fibroblasts and a high density of collagen bundles (b), and the distal part with ovoid fibroblasts and a low density of collagen bundles (c)[8].

3. The distal part, which is the most solid, is rich in chondroblasts and ovoid fibroblasts, and with a low density of collagen bundles. The fibroblasts have abundant cellular organelles indicating a high level of cellular activity **(Fig. 1.4c)**.

The complex ultra-structural organization, the variable orientation of the bundles in the ACL, and the abundant elastic system make it very different from other ligaments and tendons. The ACL is a unique and complex structure able to withstand multi-axial stresses and varying tensile strains. This specificity and complexity may explain the difficulty in reproducing the original ACL following surgical reconstruction [29].

1.2.4. Innervation

The ACL receives nerve fibers from the posterior articular branches of the tibial nerve. These fibers penetrate the posterior joint capsule and run along with the synovial and peri-ligamentous vessels surrounding the ligament to reach as far anterior as the infrapatellar fat pad.

The mechanoreceptors of the nerve fibers (Ruffini, Pacini, and Golgi-like receptors) have a proprioceptive function and provide the afferent arc for signaling knee postural changes.
The ACL reflex is an essential part of the normal knee function and is involved in the updating of muscle programs [15].

1.2.5. Vascularization

The blood supply of the cruciate ligaments is provided by the middle genicular artery. The artery originates from the anterior aspect of the popliteal artery. In its extracapsular course, it is immersed in the fat of the popliteal space and is accompanied by satellite veins.

The distribution of blood vessels within the substance of the ligament is not homogeneous. The proximal part of the ACL is better endowed with blood vessels than the distal part. A small amount of blood is supplied to the distal portion of the ACL by the infrapatellar branches of the inferior genicular arteries [27]. The coincidence of poor vascularity and the presence of fibrocartilage undoubtedly play a role in the poor healing potential of the ACL.

1.2.6. Biomechanics

The ACL plays a crucial role in joint stability. It is the primary restraint to anterior translation of the tibia relative to the femur. Under normal conditions, ACL restricts anterior shift, but in chronic ACL-deficient knees, this anterior translation of the tibia relative to the femur is four times greater than in normal knees. The ACL provides an average restraint of 82–89% to the applied anterior load at 30˚of flexion. The ACL also functions as a major secondary restraint to internal rotation, particularly when the joint is near full extension [4].

1.2.7. Clinical Significance

The ACL is the most commonly injured ligament and usually occurs during a non-contact event. The mechanism of injury often involves an athlete that is changing direction with a slight pivoting motion that introduces rotational force to a planted leg. Many patients that experience this injury report feeling and hearing a “pop” that accompanies immediate pain followed by effusion. The Lachman and anterior drawer test are popular clinical tests used to assess for an ACL injury. In the young and active population, an ACL tear is usually repaired surgically to maintain stability when participating in athletic activities. Such reconstruction aims at restoring the kinematics and stability of the injured knee, to prevent future degenerative changes [19].

1.3. THE MENISCUS

Extensive scientific investigations in the recent decades have established the anatomical, biomechanical, and functional importance of the meniscus within the knee joint. As a vital part of the joint, it acts to prevent the deterioration and degeneration of articular cartilage and the development of osteoarthritis.

1.3.1. Anatomy

The knee joint contains medial and lateral menisci situated between the corresponding femoral condyle and tibial plateau **(Fig. 1.5)**. Each is a glossy-white critical component of a healthy knee joint. The main stabilizing ligaments are the medial collateral ligament, the transverse ligament, the meniscofemoral ligaments [28].

The meniscofemoral ligaments, also known as the Humphrey and Wrisberg ligaments, connect the posterior horn of the lateral meniscus to a location near the insertion of the posterior cruciate ligament on the medial femoral condyle. Though only 46% of people have both of these ligaments, 100% of people have at least one of them [17].

Human medial and lateral menisci have distinctly different dimensions: the lateral meniscus is approximately 32.4-35.7 mm in length and 26.6-29.3 mm wide, while the medial meniscus is 40.5-45.5 mm long and 27 mm wide. Though both menisci are roughly wedge-shaped and semi-lunar, the lateral meniscus displays a greater variety in size, shape, thickness, and mobility than medial menisci. The Lateral meniscus also covers a larger portion of the tibial plateau (75-93%) in comparison to medial one (51-74%) [7].

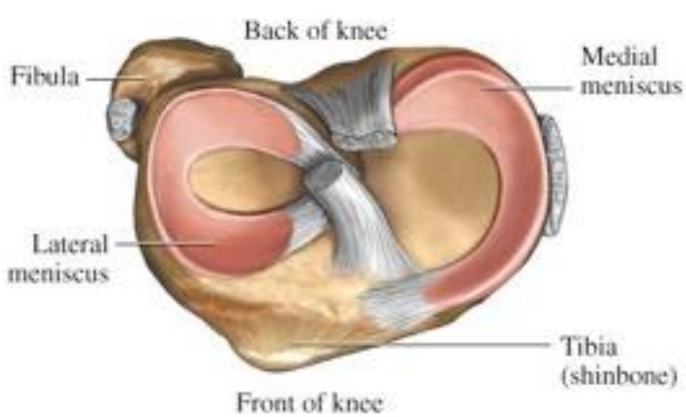

Fig. 1.5: The menisci, superior view of the right knee

1.3.2. Vascularization and Innervation

Blood supply in this tissue is of high relevance. From prenatal development until shortly after birth, the meniscus is fully vascularized. Afterward, however, vascularization appears to subside. At 10 years of age, vascularization is present in around 10-30% of the meniscus, and at maturity, the meniscus contains blood vessels and nerves only in the peripheral 10-25% of the tissue [7]. Subsequently, two distinct regions of the meniscus can be distinguished: the outer, vascular-neural region (red-red zone), and the inner, completely avascular-aneural region (white-white zone). These two areas are separated by the red-white region, which presents attributes from both the red-red and white-white regions. Critically, the healing capacity of each area is directly related to blood circulation, leaving the white region susceptible to permanent post-traumatic and degenerative lesions [3].

1.3.3. Meniscal Cells and Biochemical Content

Cell phenotype and extracellular matrix (ECM) composition render the outer portion of the meniscus akin to fibrocartilage, while the inner portion possesses similar, but not identical, traits to articular cartilage [21].

The meniscus is highly hydrated (72% water), with the remaining 28% comprised of organic matter, mostly ECM and cells [15]. In general, collagens make up the majority (75%) of this organic matter, followed by glycosaminoglycans (17%), DNA (2%), adhesion glycoproteins (<1%), and elastin (<1%) [15, 16]. The above proportions might vary depending on age, injuries, and other pathological conditions [22]. Their main function is to enable the meniscus to absorb water, whose confinement supports the tissue under compression [1].

Different collagen types exist in varying quantities in each region of the tissue. In the red-red zone, collagen type I is very predominant, while In the white-white zone, 60% is collagen type II and 40% is collagen type I [5].

1.3.4. Biomechanical and Functional Properties

The meniscus withstands many different forces such as shear, tension, and compression. It also plays a crucial role in load-bearing, load transmission, shock absorption, as well as lubrication and nutrition of articular cartilage. These multiple and complex functions require a specialized form. Since the tissue is wedge-shaped, it proves highly adept at stabilizing the curved femoral condyle during articulation with the flat tibial plateau. It has been calculated that the intact menisci occupy approximately 60% of the contact area between the articular cartilage of the femoral condyles and the tibial plateau, while they transmit >50% of the total axial load applied in the joint. However, these percentages are highly dependent on the degree of knee flexion and tissue health. In full flexion, the lateral meniscus transmits 100% of the load in the lateral knee compartment, whereas the medial meniscus takes on approximately 50% of the medial load [24].

Kurosawa et al. [16] noted that following total meniscectomy, the tibiofemoral contact area decreased by approximately 50%, therefore leading to an overall increase in contact forces by 2-3 times on the articular cartilage.

1.3.5. Clinical Significance

A meniscal tear is another very common knee injury that frequently has the same injury mechanism as an ACL tear, a pivoting motion on a planted foot. Meniscal tears may also occur in older patients as a result of degenerative changes. Sometimes the individual will notice when the injury occurs, and other times they may be unaware. It is common for a meniscal tear to accompany other knee injuries such as ligament tears. Typically, pain and effusion accompany the injury and sometimes patients complain of knee clicking, locking, and catching during activity [12].

Treatment is variable with each patient and ranges from conservative treatment to surgery. The McMurray test is the most used clinical technique to detect the presence of meniscal tears with MRI being the most accurate imaging modality [25].

1.4. THE TIBIA

The tibia is the main bone of the leg, It has proximal and distal ends, and a shaft. It is the second largest long bone in the body **(Fig. 1.6)** [28].

1.4.1. Bone anatomy

Proximal End

At the proximal end, the tibia is widened by the medial and lateral condyles. The condyles form a flat surface, known as the tibial plateau.

The medial condyle is larger than the lateral condyle. The articular surface is oval and its large pole is anteroposterior.

The central part of the articular surface is concave and contact with the femoral condyle. The flatter peripheral part separated from the femoral condyle by the medial meniscus.

On the posterior surface of the medial condyle has a groove. Many vascular foramina mark the anterior and medial surfaces.

The lateral condyle is nearly circular and articulates with the lateral condyle of the femur and in peripheral part is covered by the lateral meniscus. The central part is concave just like medial condyle and contact with femoral condyle.

The postero-inferior aspect of lateral condyle of the tibia bears a flat, circular fibular facet for articulation with the fibula.

The intercondylar area is the roughened area on the superior surface, between the two condyles. This part is elevated to form the intercondylar eminence which is the medial and lateral intercondylar tubercles.

The tibial tuberosity is a prominent projection located on the anterior surface of the proximal tibia, inferior to the condyles.

Shaft Of Tibia

The shaft of the tibia is triangular in shape with three surfaces (lateral, medial and posterior) and three borders (anterior, medial and interosseous).

The anterior border is sharp and S-shaped, in the upper part convex medially and convex laterally in the lower part. The anterior border extends from the tibial tuberosity to the anterior border of the medial malleolus.

The medial border extends from the medial condyle to the posterior border of the medial malleolus and is rounded.

The lateral border is also described interosseous border and extends from the lateral condyle to the anterior border of the fibular notch.

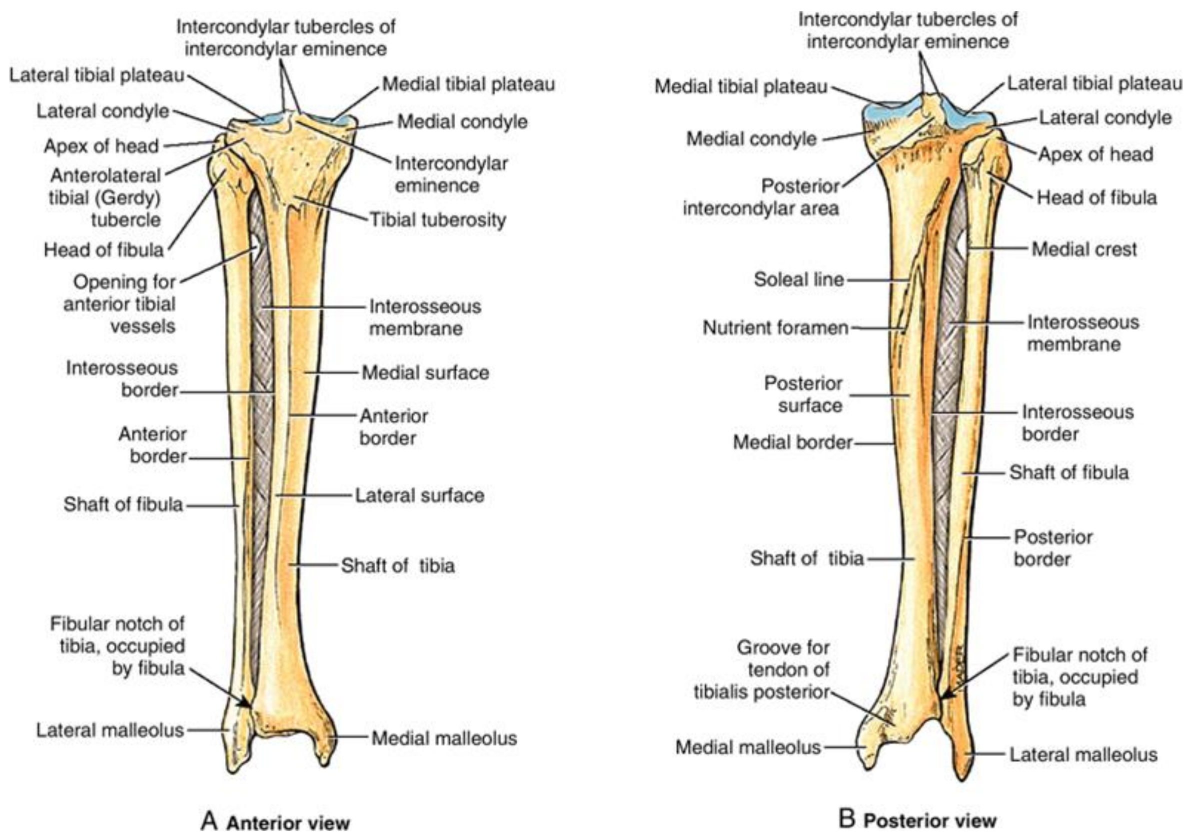

Fig. 1.6: Anatomy of the Tibia. A. anterior tibia, B. posterior view.

The lateral surface rests between the anterior and interosseous borders. In its upper three-fourths it is concave and is directed laterally, and in its lower one-fourth, it is directed forwards. The medial surface lies within the anterior and interosseous borders. It is mostly subcutaneous. The posterior surface of the tibia is in between the medial and interosseous borders. It widens in its upper part. A rough ridge described as the soleal line crosses from the fibular facet, running downwards and medially, and terminating by connecting the medial border. Below the soleal line the surfaces divided into medial and lateral parts by a vertical ridge.

Distal End

The distal end of the tibia is expanded, but lesser than the upper end. It has a downward projection on the medial side described as a medial malleolus.

1.4.2. Muscles Attachments Of The Tibia

- Tensor fasciae latae muscle insert into the Gerdy's tubercle.

- Quadriceps femoris muscle inserts into the tuberosity of the tibia.
- Sartorius muscle inserts into the pes anserinus.
- Gracilis muscle inserts into the pes anserinus.
- Semitendinosus muscle inserts into the pes anserinus.
- Horizontal head of the semimembranosus muscle inserts into the medial condyle
- Popliteus muscle inserts into the posterior side of the tibia over the soleal line.

1.4.3. Blood Supply

The tibia is blood supplied from two sources: as the main source is the nutrient artery, and periosteal vessels arisen from the anterior tibial artery [28].

1.4.4. Articulation of The Tibia

The tibia is a role of four joints. In the weight-bearing part knee joint, the tibia articulates with the femoral condyles. The tibiofibular joints provide very little movement. A proximal tibiofibular joint is a little plane joint. The joint is formed within the undersurface of the lateral tibial condyle and the head of the fibula. The distal tibiofibular joint is formed by the rough, convex surface of the distal end of the medial side of the fibula, and a rough depression on the lateral side of the tibia. The ankle joint connects the distal ends of the tibia and fibula with the proximal end of the talus [28].

1.4.5. Ossification of The Tibia

The tibia is ossified from three centers; a primary center for the shaft of the tibia and a secondary center, one for either end. Ossification starts in the center of the body, roughly the seventh week of fetal life, and gradually extends toward the extremities. The center for the upper epiphysis appears at close to 34 weeks gestation, lower epiphysis appears in the second year [28].

1.4.6. Clinical Significance

The upper end of the tibia is the commonest site of osteomylitis. The tibia is normally fractured at the junction of upper two thirds and lower one third of its shaft. The fractures in the lower third of the shaft of tibia show delayed union or non-union due to low blood supply.

1.4.7. Development of the Tibial Slope

The tibial slope is not static and changes from birth until skeletal maturity. At birth, the tibial slope is approximately 25° but decreases until skeletal growth is completed [13]. At maturity, tibial slope ranges from 0° to 20°, and the absolute value depends on the population group **(Fig. 1.7)**. Genin et al. [10] measured posterior tibial slope in a cadaveric study in Caucasian subjects and reported that the tibial slope varies between 0° and 18°.

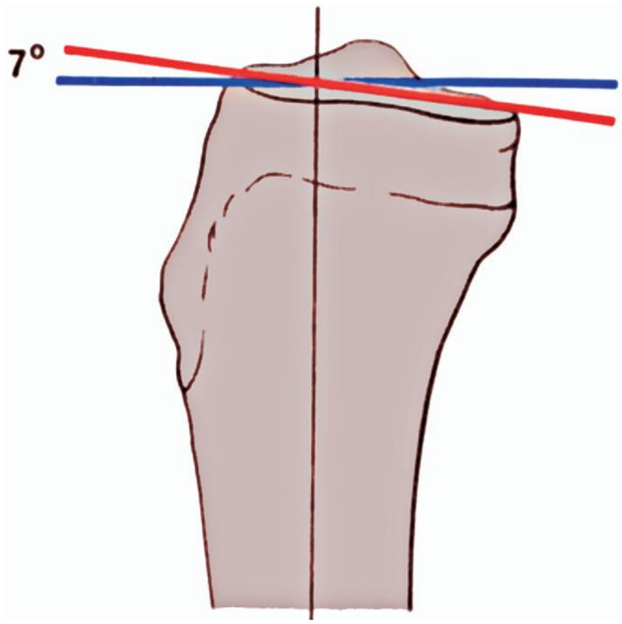

Fig. 1.7 Posterior tibial slope varies among population groups. It is defined as the angle between a perpendicular line (blue) to the shaft of the tibia (black) on a sagittal image and the inclination (red) of the tibial plateau [13].

In contrast, the average tibial slope in the Chinese population varies between 6° and 14° [6], whereas the Japanese have an average value of 11°.5-15 [20]. Meister et al. [23] measured the slope in the North American population group and found the slope to average 10°. Posterior tibial slope does not only differ between population groups, but it can also differ between the dominant and nondominant limbs of individuals [13].

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Chapter 2

REVIEW ARTICLE

EXTREME VARIABILITY IN POSTERIOR SLOPE OF THE PROXIMAL TIBIA: DIFFERENT METHODS AND TECHNIQUES FOR ITS MEASUREMENT

A Systematic Review

ABSTRACT

BACKGROUND: It has been reported that the posterior tibial slope (PTS) has an influence on the on the kinematics of the knee notably the anterior cruciate ligament (ACL), A better understanding of the significance of the PTS could improve the development of ACL injury screening and prevention programmes, and might serve as a basis for individual adapted rehabilitation programmes after ACL reconstruction.

Additionally, in several orthopedic interventions such as high tibial osteotomy, the tibial slope can result in altered knee mechanics. Therefore, an exact preoperative measurement of the posterior tibial slope is mandatory. Several methods are used on conventional radiographs, Computed tomography (CT) and magnetic resonance imaging (MRI), but until now there is no standard validated method.

PURPOSE: The purpose of this study was to report a comprehensive literature review comparing the different methods and techniques of measurement of the PTS among the conventional radiograph, CT scans, and MRI in order to help the orthopedic surgeons to establish a standard and reliable measurement method.

STUDY DESIGN: A systematic review.

METHODS: All relevant abstracts were read and articles of potential interest were reviewed in detail to determine the inclusion status for this systematic review. Information regarding methods of measurement of the tibial slope in normal and ACL-injury subjects was extracted from all included studies in a systematic fashion and classified according to the measurement technique and used modalities. The PubMed, CINAHL database and Google Scholar were searched thoroughly to identify all studies reporting a measure of tibial plateau slope and then to identify studies that met pre-stated inclusion criteria. Two authors independently extracted information involved general characteristics of the recruited studies, including principal results for each study.

RESULTS: Forty-six studies were included in this review. 23 studies used the lateral radiography, 16 MRI studies, 5 used CT Scan and 2 studies directly measured the PTS. By direct comparison, the greatest value of the medial tibial slope (MTS) for the pathological knee was achieved by the radiological studies, while the MRI studies presented the smallest values. Consequently, for the pathological lateral tibial slope (LTS), the MRI values were smaller than that of the CT studies. The most common used axis was the proximal tibial anatomical axis. The greatest values of the MTS and LTS were obtained by the anterior tibial cortex axis, while the minimum values were achieved by the tibial diaphyseal axis.

CONCLUSION: No consensus has been reached regarding the choice of the reference axis for the tibial slope measurements. With respect to the current literature, the most representing anatomical reference for the tibia was the PTAA. The midpoint method is the most frequently used for calculating PTAA. This should be the preferred methodology until a significantly more reliable and standardized protocol is defined and validated in the literature. Among the modalities used for PTS measurement, the greatest advantages of using MRI for this application is the ability to visualize the surface geometry of the articular cartilage, which represents the functional point of tibiofemoral joint, in addition to the possibility of individual measurement of the tibial slope in both compartments and their associated tissue structures.

Despite high measures of the reliability of the various methods reported in current studies, there is wide disagreement regarding the actual values of the slope that would be considered at risk of developing ACL injury. Reported tibial slope values for control groups vary greatly between studies.

In many cases, the study-to-study differences in normal tibial slope exceed the difference between controls and ACL-injured patients. The clinical utility of imaging-based measurement methods for the determination of ACL injury risk requires a more reliable technique that demonstrates consistency between studies.

Keywords:

Tibial slope, posterior tibial plateau, radiological measurement, radiography, MRI, CT scan

RÉSUMÉ

Il a été rapporté que la pente tibiale postérieure (PTS) a une influence sur la cinématique du genou notamment le ligament croisé antérieur (LCA). Une meilleure compréhension de la signification de la pente tibiale pourrait améliorer le développement du dépistage des lésions du LCA et des programmes de prévention et pourrait servir d'une base pour des programmes de réhabilitation individuellement adaptés après la reconstruction de LCA.

De plus, dans plusieurs interventions orthopédiques comme l'ostéotomie tibiale haute, la pente tibiale peut modifier la mécanique de genou. Dès lors, une mesure préopératoire exacte de la pente tibiale postérieure est obligatoire. Plusieurs méthodes sont utilisées sur des radiographies conventionnelles, des scanners et IRM, mais jusqu'à présent il n'y a aucune méthode standard validée.

Le but de cette étude était de rapporter une revue compréhensive de littérature comparant les méthodes et les techniques différentes de mesure de PTS parmi la radiographie conventionnelle, la tomographie et IRM a fin d'aider les chirurgiens orthopédiques à établir une méthode de mesure standard et fiable.

Tous les résumés ont été lus et les articles d'intérêt potentiel ont été passés en revue en détail pour déterminer sur le statut d'inclusion pour cette revue systématique. Les Informations quant aux méthodes de mesure de la pente tibiale chez des sujets normaux et LCA-blessés ont été extraites de toutes les études incluses de manière systématique, et ont classifiées selon la technique de mesure et les modalités utilisées.

Le PubMed, la base de données CINAHL et le Google Scholar ont été fouillés pour identifier toutes les études rapportant une mesure de la pente tibiale et ensuite identifier les études qui ont respecté des critères d'inclusion pré exposés. Deux auteurs ont indépendamment extrait les caractéristiques générales impliquées des études incluses (le type d'étude, les caractéristiques de l'échantillon, la modalité utilisée et les méthodes de mesure de PTS), et le résultat principal pour chaque étude.

Les conclusions principales de cet examen systématique: 46 études ont été incluses. 23 études ont utilisé la radiographie latérale, 16 études de IRM, 5 études de CT et 2 études ont directement mesuré les PTS sur l'os nu. Par la comparaison directe, la plus grande valeur de la pente tibiale Interne (MTS) pour le genou pathologique a été réalisée par les études radiologiques, tandis que

les études de IRM ont présenté les plus petites valeurs. Par conséquent, pour la pente tibiale latérale (LTS), les valeurs de IRM étaient plus petites que celui des études de CT.

L'axe le plus utilisé était l'axe tibial anatomique proximal (PTAA). Les valeurs les plus grandes de MTS et de LTS ont été obtenues par l'axe de cortex tibial antérieur, tandis que les valeurs minimales ont été réalisées par l'axe tibial diaphysaire.

Aucun consensus n'a été atteint quant au choix de l'axe de référence pour les mesures de la pente tibiale. En ce qui concerne la littérature actuelle, la plupart de référence anatomique représentante pour le tibia était le PTAA. La méthode (Midpoint) est le plus fréquemment utilisée pour calculer le PTAA. Ceci devrait être la méthodologie préférée jusqu'à ce qu'un protocole significativement plus fiable et standardisé soit défini et validé dans la littérature.

Parmi les modalités utilisées pour la mesure de PTS, les avantages les plus grands d'utiliser IRM pour cette application sont la capacité de visualiser la géométrie superficielle du cartilage articulaire qui représente le point fonctionnel d'articulation tibiofemoral, en plus de la possibilité de mesure individuelle de la pente tibiale dans les deux compartiments et leurs structures tissulaires associées.

Malgré les hautes mesures de fiabilité des méthodes diverses rapportées dans des études actuelles, il y a un large désaccord quant aux valeurs réelles de la pente que l'on considérerait en danger de développer la blessure du LCA. Les valeurs rapportées de la pente tibiale pour les groupes de contrôle varient grandement entre les études.

Dans des nombreux cas, les différences d'étude-à-étude de la pente tibiale normale excèdent la différence entre les contrôles et les patients du LCA-blessés. L'utilité clinique de méthodes de mesure à base d'imagerie pour la détermination de risque de blessure du LCA nécessite une technique plus fiables qui démonte la consistance entre les études.

FIGURES

TABLES

ABBREVIATIONS

Term	Description
ACL	Anterior cruciate ligament
ATC	Anterior tibial cortex axis
ATT	Anterior tibial translation
BMI	Body mass index
CAA	Central anatomical axis
CDC	Centers for Disease Control and Prevention
CT	Computed tomography
FSA	Fibular shaft axis
HTO	High tibial osteotomy
LTS	Lateral tibial slope
MA	The mechanical axis of the tibia
MPA	Mean of ATC+ PTC
MRI	Magnetic resonance imaging
MS	Meniscal slope
MTS	Medial tibial slope
PFAA	Proximal fibular anatomical axis
PKTD	Porto Knee Testing Device
PTAA	Proximal tibial anatomical axis
PTC	Posterior tibial cortex axis
PTS	Posterior tibial slope
SD	Standard deviation
TCAA	Tibial central anatomical axis
TDA	Tibial diaphyseal axis
TKA	Total knee arthroplasty
UKA	Unicompartmental knee arthroplasty

CONTENTS

2.1. INTRODUCTION

The anterior-posterior stability of the knee joint has been shown to be dependent on many factors. The soft tissues around the knee, including the external and internal ligaments [41], the menisci [101] and the joint capsule [108] are probably functional members that act together to support the opposing joint surfaces to afford homogenous contact and normal kinematic articulating motion.

It has been reported that the geometry of the tibial plateau, in particular, has a direct influence on the stability of the knee joint in the sagittal plane in terms of translation, the location of the instantaneous center of rotation, the screw-home mechanism, and the strain biomechanics of the important ligaments such as the anterior cruciate ligament (ACL) [47].

2.1.1. ACL INJURY PREVALENCE

Data collected by the American Academy of Orthopedic Surgeons lists ACL injury as one of the most common knee problems and ACL reconstruction ranked sixth among the most common surgical procedures performed by all sports medicine fellows. The Centers for Disease Control and Prevention (CDC) has reported that approximately 80,000–100,000 people in the United States currently undergo ACL reconstruction each year [36, 43].

Consequences of ACL injury include both temporary and permanent disabilities. Moreover, the costs of treatment of the ACL injury are very high from both patient’s health and economic points of view [43, 46, 67].
Such prevalence reflects the importance of knee surgeons to define strategies for early diagnosis and prevention of the ACL injury, based on the definition of risk factors. Any procedures able to contribute to reducing the incidence of this injury, besides the personal and athletic benefit, would probably have a significant social and economic impact.

2.1.2. MECHANISM Of ACL INJURY

Injuries to the ACL arise due to deterioration of the static and dynamic stabilizers of the knee joint. While the static stability is supplied by ligaments, menisci, joint capsule, and bony geometry, the dynamic stability is an integrated function of the neuromuscular system [97].

ACL injury occurs predominantly via non-contact mechanisms. Because of a high incidence of the long-term complications of ACL injury, including pain, impairment of normal knee function, meniscal lesions and early development of osteoarthritis [38]; many studies have been conducted to better understand the mechanisms of ACL injury and the associated risk factors contribute to increased risk for injury [39, 43, 51, 55]. While substantive research efforts have been made to improve diagnosis and treatment strategies, the long-term consequence of ACL injuries is likely osteoarthritis even in cases undergoing surgical treatment. Therefore, a great deal of the sports medicine literature has focused on the early diagnosis and prevention [63, 67].

The largest proportion of ACL injuries occurs during sports activities involving deceleration, jumping, or twisting. These injuries can occur as a result of excessive valgus stress, forced external rotation of the femur on a fixed tibia or excessive hyperextension typically as an athlete lands or pivots on the Leg [27, 50].

An ACL injury leads to an interruption in the athletic career, and in some cases, former athletic performance cannot be reached even following successful reconstruction. Therefore, evidence-based preventive measurements should be provided as at least advanced treatment approaches [97].

2.1.3. PREVENTIVE MEASURES AND IDENTIFICATION OF RISK FACTORS

Several retrospective studies have identified the development of degenerative joint disease in knees after ACL injury despite surgical reconstruction. Therefore, it is not sufficient to emphasize only prompt recognition and appropriate treatment algorithms, but orthopedic surgeons must develop prevention strategies and verify them using scientific programs. An important step to prevent the development of the injury, is the identification of athletes at increased risk of non-contact ACL injury [34, 43, 52].

Assessment of ACL injury risk factors is the first step in the development of injury prevention. Although the etiology of ACL injuries is still uncertain, many risk factors have been proposed. In addition to the individual biomechanical, anatomical and hormonal factors, environmental factors may also increase the risk of injury [43, 48, 58, 87].

Generally, these risk factors may be divided into extrinsic and intrinsic factors. The former can be modified by targeted intervention according to the sport, such as improving hamstring and quadriceps strength [26], proprioception [70] and neuromuscular control patterns [3]. Whereas intrinsic risk factors are often inherent to an individual person such as ligament structures and anatomical variations that cannot be modified [11, 80]. However, preventative strategies that aimed at modifying the extrinsic factors, had little effect on the general rates of ACL injury [35].

Recently in the literature, there has been a greater focus on specific anatomic risk factors. These include an increased posterior tibial slope [13, 33, 83, 99, 111], a shallow medial tibial plateau with a steep lateral slope, [48, 103, 106], and a smaller ACL volume [87].
On the femoral side, a narrow intercondylar notch dimension has been previously reported. Athletes with narrow intercondylar notches of the femur are more likely to tear the anterior cruciate ligament than athletes with wide intercondylar notches [25]. The smaller the intercondylar notch; the smaller the cross-sectional area of the ACL. The impingement of the ACL at the medial wall and superior roof of the notch may be the reason for the increased incidence of ACL rupture in patients with a small intercondylar notch [25, 30, 100].

Variations in the magnitude of the quadriceps femoris angle (Q angle), the degree of static and dynamic knee valgus, foot pronation, and body mass index (BMI) have also been thought to be associated with ACL injury risk [43].

2.1.4. POSTERIOR TIBIAL SLOPE

While laxity of the knee joint is influenced by various structures, including the cruciate and collateral ligaments, the menisci, the joint capsule, and the surrounding muscles and tendons, it is also affected by the articular surface geometry of the femur and tibia [16, 26, 88, 101].

The tibial plateau geometry, especially its posterior inclination, the so-called posterior tibial slope (PTS), has been recently the interest of various investigations as one of the most often stated anatomic structures that could cause ACL injuries.

PTS is defined as the angle between the line perpendicular to the mid-diaphysis of the tibia and the posterior inclination of the tibial plateau, which has been applied in most studies related to ACL injuries [41, 122].

The direction of weight transmission from the femur to the tibial condyle to the trochlea tali on the foot, overlaps with the tibial diaphyseal anatomical axis, which represents the ideal reference axis to measure PTS, however, due to its position, difficult to obtain by routine diagnostic modality [107], for that reason many alternative axes and methodologies presented for measurement of the tibial slope and we will discuss them later in details.

It has been suggested that the slope plays a role in static stability, and a greater tibial slope is claimed to be one of the ACL injury risk factors in recent years [43, 48, 106].
Additionally, many studies reported that the tibial slope has a direct influence on sagittal plane laxity and therefore contributes to the loading behavior of the ACL [13, 26, 35, 41, 59, 111].
However, despite that the PTS has been increasingly studied as a potential risk factor for ACL injury, the literature reveals widely varied results regarding its measurements [54, 56, 66, 67, 94, 103, 116].

2.1.5. THE BIOMECHANICAL ASPECT OF THE POSTERIOR TIBIAL SLOPE

Biomechanically, a higher tibial slope in the presence of a compressive load will generate a higher anterior shear component of the tibio-femoral reaction force, resulting in increased anterior motion of the tibia relative to the femur. Because the ACL is the primary restraint against this type of motion in the knee, it logically follows that an increase in PTS will influence the in situ forces of the ACL, and consequently inducing stretching and rupture of the ACL [26, 35, 43]. This hypothesis was first stated by Butler et al. in 1980 [31].

This mechanism has been observed in cadaver models [101, 112] as well as in living subjects [6, 26]. In a cadaveric study by McLean et al. the mean peak strain in the anteromedial bundle of the ACL was found to be directly proportional to anterior tibial acceleration during a simulated jump-landing task. More remarkably, the tibial slope was significantly correlated with both peak anterior tibial acceleration and peak anteromedial bundle strain [82].

In a radiographic in vivo study, Dejour and Bonnin have established that an increase of every 10˚ in the tibial slope is associated with a 6 mm increase in anterior tibial translation (ATT) in both ACL-deficient and healthy knees [26].

Other biomechanical studies have demonstrated increased ACL strain or ACL rupture after isolated or combined axial tibiofemoral compression and quadriceps loading [28, 37, 71, 79, 85, 117]. These mechanisms have been attributed to the increased tibial slope.

By using a musculoskeletal computer model of the lower limb, Shelburne et al. [99] found that the changes in ATT, tibial shear force, and the cruciate ligament force attributed to the changes in PTS. Similar results achieved by Shao et al. [98] from their biomechanical model, in both healthy and ACL-deficient knees.

Other studies found that the anterior translation of the tibia relative to the femur resulted from the increased tibial slope which created an anteriorly directed shear force just as the higher pivot shift grades when a compressive tibiofemoral load or a quadriceps muscle force is applied to the knee joint [24, 112, 115].

2.1.6. THE ROLE OF PTS IN ACL INJURY REMAINS ELUSIVE

Despite a large number of studies that correlate the PTS positively to the ACL injury, the issue remains controversial. Many studies have investigated the link between tibial slope and the risk of ACL injury, and most found a positive association. However, the magnitude of the association has been varied between studies. [9, 13, 48, 54, 56, 66, 67, 103, 104, 106, 110, 111, 116].

Conversely, other studies do not show a correlation between these two parameters [60, 83]. Moreover**,** Giffin et al. [41] have reported that a small increase in the tibial slope does not influence anterior tibial translation and that it may represent a protective factor in ACL-deficient knees. In another study, the authors have pointed out that the tibial slope is an important parameter in the treatment of posterior and posterolateral knee instabilities [42].

2.1.7. CLINICAL RELEVANCE OF THE CORRELATION BETWEEN PTS AND ACL INJURY

This relationship between the tibial slope and ACL strain might be of clinical importance of many aspects.
In ACL-healthy subjects, a greater tibial slope might represent a risk factor for non-contact ACL injury because of increased ATT and ACL strain during axial tibiofemoral compression and quadriceps muscle loading [6, 26]. A better understanding of the role of the tibial slope in ACL injuries might help to improve ACL injury screening and prevention programmes and consequently reduces the prevalence of these injuries.

In ACL-insufficiency patients, a steeper tibial slope might correlate with greater instability due to an increased ATT [98, 99]. The tibial slope could, therefore, serve as a measurable parameter to identify patients who would more likely to undergo early ligament reconstruction.

During early weight bearing after ACL reconstruction, a steep tibial slope might place increased load on the healing graft and fixation material and potentially increase the risk of early elongation or acute failure. Similarly, late failure might occur due to repetitive overloading and subsequent elongation of the graft. Improved knowledge about the effect of the tibial slope on the graft after ACL reconstruction might serve as a basis for individually adapted postoperative rehabilitation programmes [35]. These preventive measures may include slope-modifying osteotomy as a therapeutic option to prevent graft failure in patients with a steep tibial slope undergoing ACL reconstruction.

2.1.8. VARIABLES METHODOLOGIES AND MODALITIES FOR THE PTS MEASUREMENTS

As mentioned before, it is difficult to realize the ideal reference axis for the measurement of the PTS as many alternatives have been published. The main purpose of the this work is to provide an overview of the different methodologies used to measure the PTS. To this day, no uniform method exists to measure the tibial slope because of different longitudinal reference tibial axes currently used [14, 26, 63, 80, 89, 120].
Besides anatomical axes, such as the proximal tibial anatomical axis (PTAA), the proximal fibular anatomical axis (PFAA) or a tangent along the anterior and posterior tibial cortices [14, 89], the mechanical axis of the tibia (MA) has also been used [120]. These different axes are not parallel, and values of the tibial slope within one tibia differ depending on the axis used [23,113, 120].

Furthermore, despite its frequent use, there is little consensus on the ideal medical imaging technology for measuring the posterior tibial slope.
The conventional lateral radiograph is said to be inferior to CT scans for determining the tibial slope, primarily due to the difficulty of perfect lateral alignment; however, several studies have addressed the question of whether a steep tibial slope on lateral radiographs represents a risk factor for non-contact ACL injury [13, 21, 54, 83, 104, 111, 116, 120].

The biomechanical impact of the tibial slope, however, might be even more complex, as the characterization of the tibial plateau surface geometry with a single slope on lateral radiograph likely represents an insufficient approximation of its three-dimensionality [47].

Further additional anatomical details could be achieved by MRI-based studies [9, 48, 56, 66, 103, 106, 110]. Although, the MRI is not a standard preoperative modality in all orthopedic procedures.

Because of the substantial differences between the slopes of the medial and lateral compartment [21, 46, 57, 61, 68, 120]. The axial compression of a knee with a higher lateral tibial slope (LTS) compared with a medial tibial slope (MTS) may cause greater anterior displacement of the lateral compartment of the tibia compared with the medial one, creating a net internal rotational movement of the tibia with respect to the femur, which may increase loading on the ACL [10, 81, 103, 106, 115].
However, despite several reports relating increased posterior slope of the medial or lateral tibial plateau to the ACL injury, the level of risk posed by this intrinsic factor remains unclear due to the wide variability in the methodology of these studies.

2.1.9. THE AIM OF THE WORK

The purpose of this article is to present a wide review of original research studies dealing with the measurement of the posterior tibial slope and to compare their methodologies and consistencies. An improved understanding of this topic may have important public health and clinical implications in the diagnosis and management of ACL injuries.

2.2. MATERIALS AND METHODS

The goal of the review was to identify all existing literature that involves studies measured the PTS published in the English language with enough information about the used technique and the modality of assessment.

2.2.1. INFORMATION SOURCES AND SEARCH STRATEGY

ELECTRONIC SEARCH

An expanded electronic search was performed in the literature, it was conducted using the PubMed (MEDLINE), Cochrane database and the Google scholar up to December 2016 (no start date). The following search terms were used [(Tibial slope OR Posterior Tibial Plateau) AND/OR (Radiological Measurement OR Radiography) OR MRI, OR CT scan AND/OR (Anterior Cruciate Ligament OR ACL)].

OTHER SEARCH METHODS

The reference lists of all included articles were reviewed to search for potential studies that are not previously identified.

2.2.2. STUDIES SELECTION

All prospective, cross-sectional or retrospective prognostic human studies measuring the posterior tibial slope were evaluated for eligibility.

Studies were included if they were: written in English language, level of evidence between I and IV, and contained results specified for tibial slope measurement.

Studies were excluded if an unrelated surgical procedure was performed before the PTS measurements, or if the study reported patients or control groups with diffuse chondral lesions or bone deformities.

Studies were also required to report the measurement of specific tibial anatomical index or indices. Studies not including enough information regarding the methods and modality were excluded.

Studies chosen for full article review were included in this review if they met all of the above inclusion criteria and none of the exclusion criteria. All references from each article included for full review were subjected to the above criteria to ensure a thorough analysis of the literature.

Review articles, systematic reviews, and meta-analyses were not included, but reference lists were examined to ensure completeness of relevant studies. The studies compare the sex difference of the PTS between male and female and those comparing the difference of the slope between the two tibial compartments were reviewed in detail to assess for intragroup comparison.

ELIGIBILITY CRITERIA

All titles and abstracts were read and articles of potential interest were reviewed in detail of their full text by the authors, to decide on inclusion or exclusion from this review.
In cases of doubtful articles, all authors reviewed and discussed the study and a final decision is taken by consensus.
In all cases where the information regarding the method of calculating the tibial was not provided, a contact with the corresponding author was attempting to determine the technique used.
Studies were considered eligible if they met the following criteria:
(1) The study wrote in the English language.
(2) The study performed on a population with otherwise healthy knees or comparative studies contain a control group.
(3) The cadaver studies were included.
(4) The measured parameters were the PTS, MTS, and/or LTS.
(5) Mean ± standard deviation and sometimes the range in both injury group and the control group were reported directly or by calculated from the data.
(6) A non-related surgical procedure such as total or partial knee arthroplasty or high tibial osteotomy (HTO) was performed before the PTS measurements.
(7) Studies on artificial bones or animals were excluded.

2.2.3. DATA COLLECTION PROCESS

Information regarding methods and technique for PTS measurement was extracted by the authors from all included studies in systematic fashion.
Data extraction involved the general characteristics of the included studies:

- Type of study, names of the authors, the year of publication, characteristics of the sample (including age, sex, height weight, and BMI if available)
- Methodological aspects of the recruited studies
- Type of modality including lateral radiograph, CT, MRI or direct measurement.
- The referred anatomical tibial axis, the technique of calculating the corresponding axis, and the principal results of the parameters.

One author (A.E) performed all data extraction, which was then verified by two authors (K.E, A.B). Any disagreements were resolved by discussion.

Data were recorded in the following order: first author's name, year of publication, study design, types of sample, mean age and gender ratio, modality, reverence axis used measurement methods, and values of the calculated parameters.

2.2.4. STATISTICAL ANALYSIS

Statistical analysis was performed using SPSS for Windows (version 11.5; SPSS, Chicago, IL, USA). Microsoft Excel was used to classify the studies in tables according to the modality and to calculate statistical values of the parameters of interest and also to create descriptive diagrams. Continuous variables were calculated as the mean ± standard deviation and categorical variables were reported as count and percentages.

2.3. RESULTS

2.3.1. THE INCLUDED STUDIES

The literature search elicited a total of 730 references, from which 366 were duplicates. A total of 364 studies were reviewed in full text, and another 310 were excluded **(Fig. 2.1)**. 54 studies were included in the review, of which 12 were removed because of non-relevant parameters. Finally, 4 articles were added after reviewing the reference lists of included studies. Therefore, 46 articles met the final inclusion criteria for the current systematic review.

2.3.2. CHARACTERISTICS OF THE STUDIES

Of the 46 studies, five of them were prospective studies. The sample includes also 18 case-control studies, 16 diagnostic longitudinal cohort studies, 4 anatomical studies, 6 cadaveric studies, and two biomechanical studies work on the loading behavior of the knee joint. Eleven studies compare different methodology for PTS measurement and three studies compare the posterior tibial slope between male and female.

The approximate number of participants involved in the 45 studies was 6161 (some studies did not specify the total number of participants included), although it is likely that some subjects were employed for more than one study published by the same group of authors. In addition, some studies used cadavers or naked bones.

For each study, Continuous variables were calculated as the mean ± standard deviation and categorical variables were reported as count and percentages.

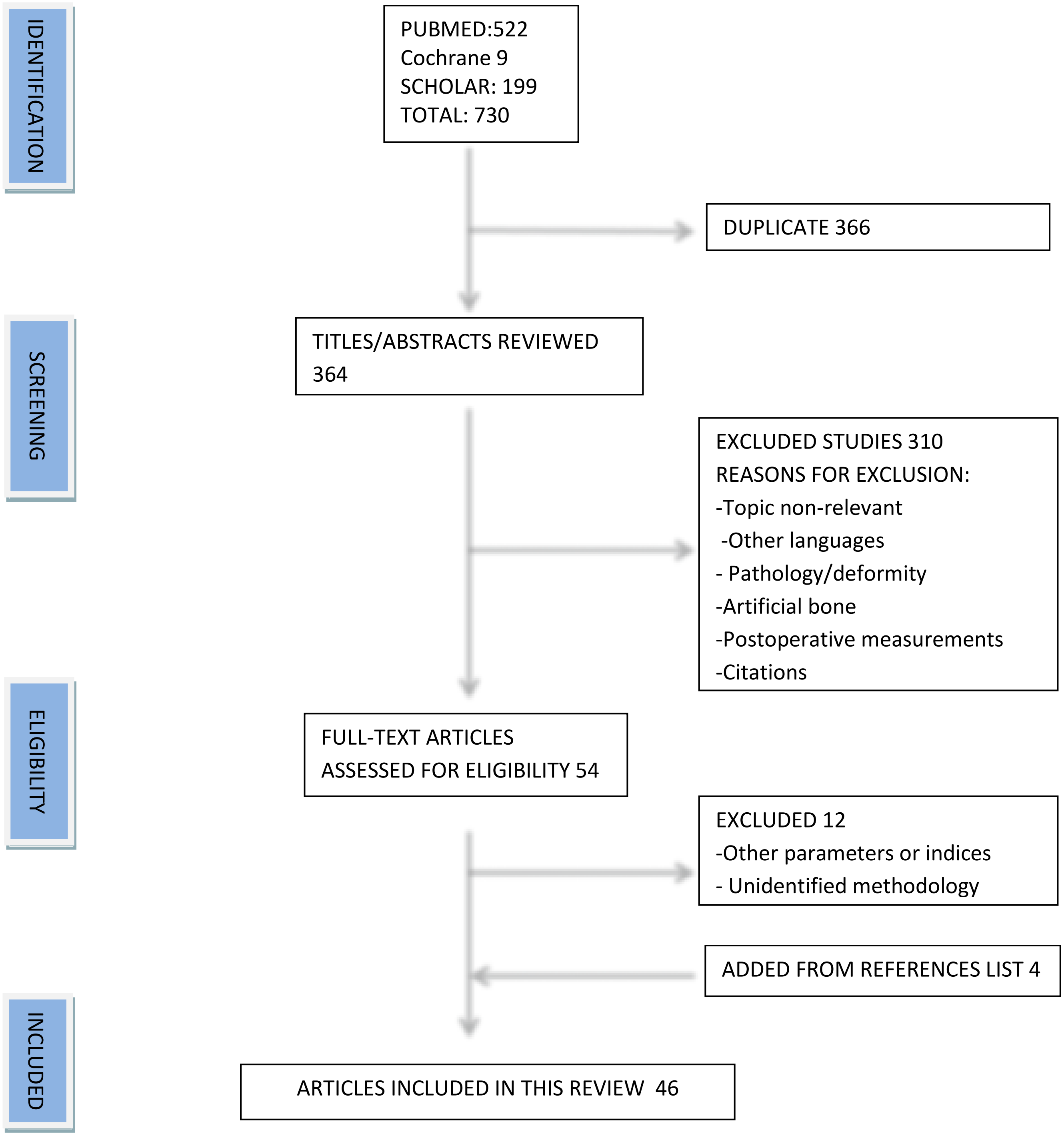


Fig. 2.1: A flowchart showing the map of study selection

2.3.3.THE COMPARISON BY THE MODALITY TYPE

Among the recruited papers, there were 23 radiological studies, 16 MRI studies, 5 CT studies, and two studies directly measured the PTS on the naked bone. However, there are some methodological studies used more than one modality. **(fig. 2.2)**

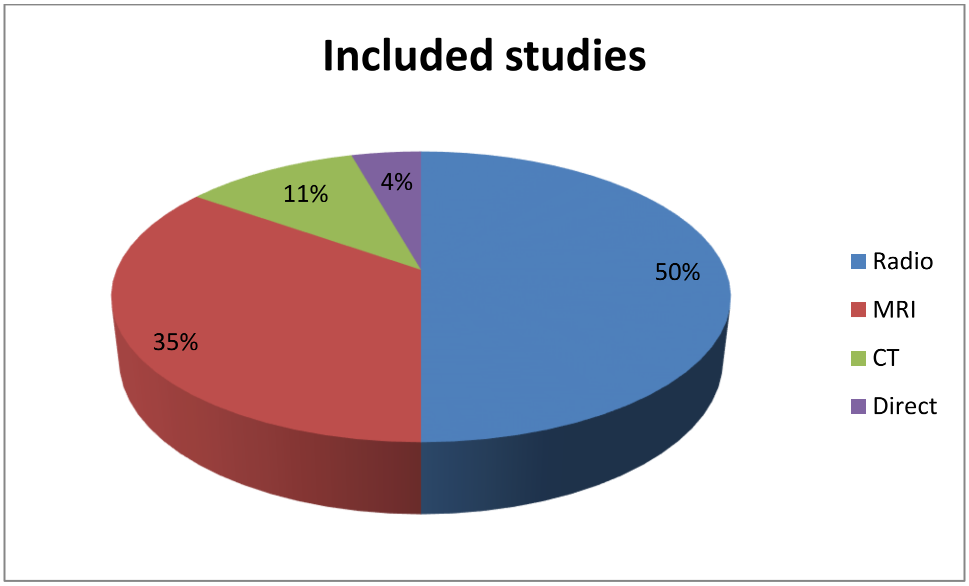


Fig. 2.2: The percentages of the included studies according to the modalities

The following **tables (2.1, 2.2, 2.3, 2.4)** show the methodological parameters of the included studies according to the modalities. To facilitate interpretation and comparison of the data, the examined groups involving both the ACL injured groups as well as the patients with knee arthrosis.

Table 2.1: Summary of the methodological parameters for the radiological studies.

Parameters	**MTS***(EXAMINED)*	**MTS** *(CONTROL)*
MEAN	9.53	9.20
SD	3.05	3.65
MIN	5.5	5
MAX	13.8	14.7

Table 2.2: Summary of methodological parameters for the MRI studies.

Parameters	**MTS**(*EXAMINED)*	**LTS** *(EXAMINED)*	**MTS**(*CONTROL)*	**LTS**(*CONTROL)*
MEAN	6.59	6.56	6.28	5.67
SD	3.54	2.73	2.87	2.42
MIN	-1.8	1.8	-2.9	-0.3
MAX	11	12	10.7	10

Table 2.3: Summary of the methodological parameters for the CT studies.

Parameters	**MTS**(*EXAMINED)*	**LTS** *(EXAMINED)*	**MTS**(*CONTROL)*	**LTS**(*CONTROL)*
MEAN	8.37	7.80	9.41	9.93
SD	2.33	1.42	1.85	1.95
MIN	4.8	5.3	6	6.3
MAX	12	9.6	12.9	13.6

Table 2.4: Summary of the methodological parameters for the direct method.

Parameters	**MTS**(*CONTROL)*	**LTS**(*CONTROL)*
MEAN	8.30	7.44
SD	1.81	0.47
MIN	7	6.9
MAX	10.7	8

By direct comparison, the greatest value of the MTS for the pathological knee was achieved by the radiological studies, followed by the CT studies, while the MRI studies presented the smallest values. Consequently, for the pathological LTS, the MRI values were smaller than that of the CT studies.

For the normal MTS and LTS, the greatest values achieved by the CT and radiological studies, and similar to the pathological parameters, the MRI represented the smallest values. Comparing the two sides, the MRI and studies of direct measurement revealed that the MTSs were larger that the laterals, conversely, the LTSs were the greater in the CT studies.

2.3.4. THE COMPARISON ACCORDING TO THE REFERENCE AXIS

Regarding the reference used, the included studies used one or more of the following axes:

- Proximal tibial anatomical axis(PTAA)
- Anterior tibial cortex axis (ATC)
- Posterior tibial cortex axis (PTC)
- Tibial diaphyseal axis (TDA)
- Proximal fibular anatomical axis (PFAA)
- Fibular shaft axis (FSA)
- Mechanical axis (MA)
- Tibial central anatomical axis (TCAA)
- Mean of ATC+ PTC (MPA)

The most common axis used was the PTAA followed by TDA. While the MPA and TCAA used only in on study [113, 120 respectively], there is similar frequency of use for the ATC and PTC. The frequency of the used axes among the studies are shown in **Figure (2.3)**.

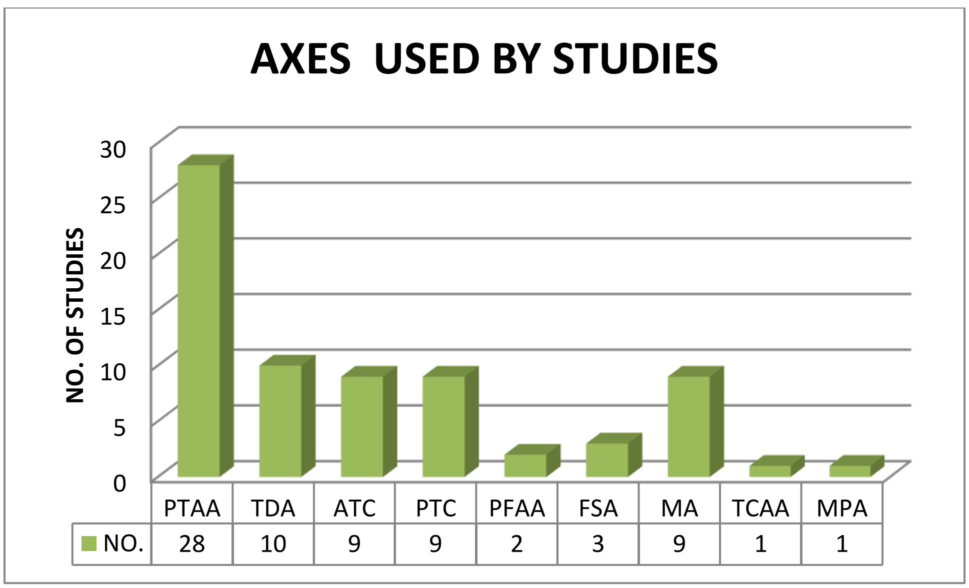


Fig. 2.3: shows the frequency of the use of the axes by the involved studies

2.3.5. COMPARISON OF THE TIBIAL SLOPES IN NORMAL POPULATIONS USING DIFFERENT AXES

The following **table (2.5)** shows the mean values of the medial and lateral tibial slopes in normal subjects of all studies. However, some axes have been used only in samples with osteoarthritic knee or with a ligament injury.

The greatest values of the MTS and LTS were obtained by the ATC, while the minimum values were achieved by the TDA. Additionally, regarding the MTS, the PTC and MA gave similar results and the values of the PFAA and MPA were also very close.

This database could be used as a reference for the future studies by helping in the selection of the proper reference axis and in comparing the results individually with the previous investigations using the same methodology.

Table 2.5: Summarizes the tibial slope values according to the axis used in all studies. MTS: medial tibial slope, LTS: lateral tibial slope, SD: Standard deviation.

AXIS	MTS (Mean ± SD)	LTS (Mean ±SD)
PTAA	8.4±2.3	6.3±1.82
TDA	6.8±3.3	5.3±3.1
ATC	12.65±1.5	13.6
PTC	7.21±1.2	6.3
MA	7.19±0.3	7.67±0.6
FSA	8.23±3.51	-
PFAA	9.54±3.62	-
MPA	9.4±2.2	9.9±2.9

2.3.6. INJURED VERSUS UNINJURED GROUP COMPARISONS

The sample involved 17 studies reported PTS measurement between ACL-injured and control subjects. The medial tibial slope was the most commonly reported measure of the tibial slope, especially in the radiological studies. Nine of these studies were performed on lateral radiographs, while eight were performed in the MRI. Four of those on lateral radiographs reported significantly higher MTS in ACL-injured patients compared with controls [13, 104, 116, 123]. However, in two studies, the difference was only statistically significant for the female subjects between the injured and control groups [54, 111].

Of those performed on MRI, one study reported a significant difference in both LTS & MTS between groups [103]. Another two studies found significant difference only in LTS [66, 106]. Moreover, in the study of Hashemi et al. [48], the female ACL-injured cases had increased LTS compared with the uninjured controls, while male cases had increased both LTS and MTS compared with controls. These differences were seen only between men and their counterparts in one study [9] and between women and their counterparts in another study [110]. It is worth noting that most of the studies matched for age and gender between the injury group and the control group.

2.4. DISCUSSION

Injuries to the ACL occur predominantly due to impairment of tibiofemoral joint stability, which is provided by static and dynamic stabilizers. The dynamic stability is an integrated function of the neuromuscular system while the soft tissues and bone morphology providing the static stability of the joint [97].

2.4.1. ACL INJURY RISK FACTORS

Evaluation of ACL injury risk factors is the first step in the preventive measures and it has been attracting a great deal of interest in the sports medicine and traumatology communities. Appropriate methods that enable predicting which patients could benefit from preventive strategies are most welcome [94].

Although the etiology of ACL injuries is still undetermined, many risk factors have been proposed. In addition to the individual biomechanical, anatomical and hormonal factors, environmental factors may also increase the risk of injury [43, 48, 58, 102].

Recently, new trends related to the biology of graft incorporation and ligament reconstruction process have also improved the ability to prevent postoperative complications such as excessive graft elongation, pullout, or slippage [84].
Recognizing all the previous, it seems mandatory to put similar efforts focused on prevention strategies.

2.4.2. THE POSTERIOR TIBIAL SLOPE AS A RISK FACTOR

Apart from the intercondylar notch, the PTS is one of the most often known anatomical structures that may cause ACL injury. An increased PTS has been retrospectively linked with a greater ACL injury risk [9, 54, 67, 103, 104].

The PTS affects knee stability, the maximal joint flexion, the resting position, and the tension placed on the cruciate ligaments of the knee [1, 42, 49, 53, 75, 113, 118].

By examining the current literature, there is some evidence that a steep tibial slope on lateral radiographs represents a risk factor for non-contact ACL injury [13, 104]. Correspondingly MRI based studies indicate that an increased lateral tibial slope might be particularly responsible for this injury mechanism [48, 81, 103, 106].

Several studies compared the tibial slope in patients with noncontact ACL injury and control [13, 48, 56, 83, 106, 110, 111]. Terauchi et al. [110] reported in their cross-sectional study that large posterior tibial slope is correlated with noncontact ACL injury in the female. Others also found in their case-control study that female patients with noncontact ruptured ACL had a significantly greater slope than did the controls [54, 111]. Hashemi et al. [48] reported significantly increased tibial slope in injured cases compared to uninjured ones. Stijak et al. [106] measured the tibial slope in both sides of the tibial plateau in ACL injured patients, and in subjects complaining of patellofemoral pain with otherwise healthy knees. They reported greater lateral tibial slope in ACL ruptured patients. Consequently, Brandon et al. [13] found greater tibial slopes in ACL injured patients and stated that the higher tibial slope increases the risk of ACL injury.

Whereas two of these studies, comparing the tibial slope value in patients with noncontact ACL injury and a control group consisting of patients with patellofemoral pain syndrome, found no difference between groups However, it was shown that arthritic changes could affect the correct measurements of the tibial slope in patients with patellofemoral pain [56, 83].

2.4.3. THE BIOMECHANICAL BASIS FOR AN ASSOCIATION BETWEEN PTS AND ACL INJURY

One of the important findings of this review is that both increased MTS and LTS were considered as risk factors for ACL injury. There may be several possible explanations for this correlation.

The biomechanical basis for an association between posterior tibial slope and ACL injury risk has been defined in the literature.

Numerous studies have demonstrated that increased tibial slope has an adverse effect on knee kinematics [17, 42, 74, 91]. An increased posterior tibial slope has been linked to greater peak ACL strain during a dynamic landing [72, 82] as well as greater ATT [26, 98, 99]. Furthermore, Physiological internal rotation at the beginning of flexion occurred primarily as a result of marked anterior displacement of the lateral tibial plateau, which in turn, imparts considerable stress on the tensioned ACL [15, 106].

Many radiological studies have demonstrated that there is a linear relationship between tibial slope and tibial translation during unilateral weight bearing; that is, the greater the posterior tibial slope, the greater the anterior tibial translation, in both ACL-healthy and ACL-deficient knees **(Fig. 2.4)**.

By using lateral radiograph, Dejour and Bonnin [26] demonstrated a 6-mm translation for every 10° increase in PTS in ACL-deficient patients and intact knees. Furthermore, the ATT was bigger on the lateral than on the medial tibial compartment in both normal and deficient knees**.**

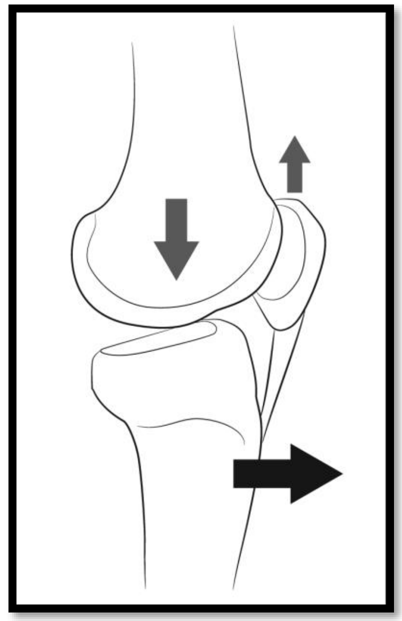


Fig. 2.4: Demonstration of the biomechanical effect of posterior tibial slope. In the knee with the increased PTS, the effect of the tibiofemoral compressive load (down arrow) and the force of the quadriceps muscle (up arrow) results in an anteriorly directed shear force, which causes an anterior translation of the tibia relative to the femur (right-facing arrow) [109].

Similarly, Giffin et al. [41] demonstrated an anterior shift in the resting position of the tibia from 3.6 mm in full extension to 2.3 mm in 120° flexion when the tibial slope was increased by 4.4° in cadaveric knees.

McLean et al. [82] reported that PTS in vitro was associated with increased anterior tibial acceleration. Furthermore, they found that strain on the anteromedial band of the ACL is proportional to anterior tibial acceleration upon impact simulating a single-legged landing.

In another study, these authors reported significant associations between medial and lateral posterior tibial slopes and peak knee abduction moment, a prospectively established predictor of ACL injury risk, in healthy active women [81]**.**

Since the ACL is the primary restraint against the ATT. Therefore, the tibial plateau slope may influence the in situ forces of the ACL [35].

However, the data are conflicting, perhaps due to the high Inter-individual variability of the tibial plateau and the imprecise measurement methods on lateral radiographs. It is found that the rotation of the tibial shaft in the x-ray beam may induce an error of as much as 14˚ and even in the ideal true lateral position an error greater than 5˚ has been reported [122].

Stijak et al. [106] by comparing a group with an ACL injured patients with a control group of patella-femoral pain, found that the lateral tibial slope had a significantly higher value in the examined group than in the control. The ATT during flexion was greater on the lateral tibial plateau. This can explain why the additional increase in the tibial slope results in greater internal rotations of the lower leg and subsequently imparted stress on the ACL that could result in its rupture.

An increased LTS relative to the medial one can influence dynamic landing biomechanics by pairing knee abduction with internal tibial rotation [81, 92, 103]. These studies emphasize the importance of accurate, repeatable separate measurements of PTS in both compartments for clinical interventions.

The PTS is believed to influence sagittal laxity of the knee joint and thereby affect the loading behavior of the ACL. Previous studies have reported that steep tibial slope might have adverse impacts on the ACL-intact, ACL-insufficient and ACL-reconstructed knee joint**.** Kawakami et al. [64] observed changes in the dynamic loading after decreasing the tibial slope using a closed wedge osteotomy.
Additionally, Shelburne et al. [99] and Shao et al. [98] used electromyography-driven computer modeling to observe the effect of the tibial slope on dynamic bony contact and ACL loading. Their results demonstrate increased force transmission through the ACL during standing and gait with an increase in the tibial slope.
In a cadaveric study, Torzilli et al. [112] demonstrate that the application of a compressive load to the knee produces an anteriorly directed shear force that results in an anterior shift of the tibia relative to the femur. The displacement was greater in ACL-sectioned knees than in intact knees.

The degree of the tibial plateau is also one of the important considerations in orthopedic surgery, in arthroplasty, as the natural PTS should not be modified, an inappropriate cutting angle of the PTS results in failure of the prosthesis and posterior cruciate ligament strain [5, 114].

From all aforementioned biomechanical studies, one can hypothesize that the increased tibial slope is able to produce an anteriorly directed shear force component when a compressive tibiofemoral load or a quadriceps muscle force is applied to the knee joint, resulting in an anterior translation of the tibia relative to the femur.

This potentially exposes the ACL to higher forces during activity and, therefore, correspondingly increases the risk of ACL injury during dynamic tasks [54]. In other words, a large tibial slope can lead to a larger anterior tibial translation via stress to the knee joint and consequently induce stretching and rupture of the ACL which could indeed affect the A-P knee stability [41, 122].
A better understanding of the significance of the tibial slope as a measurable parameter, may help to prevent ACL injuries and to improve their treatment strategies.

2.4.4. DIFFERENT METHODS FOR CALCULATING THE POSTERIOR TIBIAL SLOPE

The posterior tibial slope is commonly defined as the angle between a tangent line fit to the most superior points in the posterior-inferior surface of the tibial plateau and a perpendicular line to tibial anatomical reference line.

Reliable clinical measurements of the posterior tibial slope are important for understanding ACL injury mechanisms. From our database, It is well documented that the ACL-injured individuals commonly have a greater posterior tibial slope than the healthy ones.

While most of our included studies reported that tibial slope values are greater in ACL-injured than non-injured subjects, there is considerable inconsistency regarding the values of the slope that would be considered at risk. Some of the inconsistencies in these reports may be attributed to the use of different measurement methodologies.

For assessment of the PTS, there is high-degree measurement error can exacerbate the variability of the observed data. Some of the incongruity might result from a mismatch in subject selection and how the non-contact ACL injury was defined. Another important reason is the diversity of measurement methods. All of the referenced data were assessed by using different methods. The medial and lateral tibial slopes in an individual are not necessarily similar, and the variability among individuals is high [61, 106]. The greater the variability of a parameter within a population, the broader will be the range of the observed data. With different methods used to assess an already variable parameter, the natural variability is additionally intensified.

Reflecting its importance, the posterior slope was adopted in the radiographic evaluation of the American Knee Society and reported in most of the studies that involve the sagittal alignment of the tibial component in total knee arthroplasty (TKA) [53, 68, 95, 118]. However, despite its frequent use, there is little consensus on the ideal reference for measuring the PTS, and many studies did not reveal detailed information of the reference used in the study [21, 68, 53, 80].

These variable methodologies making the comparison of the results among different studies more difficult.

2.4.5. VARIOUS ANATOMICAL AXES USED FOR MEASUREMENT OF PTS

By analysis of the current literature, Several methods have been defined to measure medial tibial slope based on lateral radiographs [14, 20, 40, 50, 61, 63, 80, 120]. They all depend on the angle between the tangent to the tibial plateau and the perpendicular direction to each of the following anatomical axes **(Fig. 2.5)**:

1- Tibial proximal anatomical axis (PTAA)
2- Tibial longitudinal diaphyseal (Shaft) axis (TDA)or(TSA)
3- Posterior tibial cortex (PTC)
4- Proximal fibular anatomical axis (PFAA)
5- Fibular shaft axis (FSA)
6- Anterior tibial cortex (ATC)
7- The mechanical axis (MA)

The most common axis used was the PTAA followed by TLA, while the MPA and TCAA used only one time [113, 120 respectively]. However, no uniform method exists to measure the tibial slope because different longitudinal tibial axes are used, different posterior tibial slope values have been determined using various radiographic techniques and vertical tibial axes.
Depending on the reference axis chosen, a slope may change by five degrees where the greatest values of the MTS and LTS were obtained by the ATC, while the minimum values were achieved by the TLA. These results are consistent with previous studies [14, 46].

Despite an abundance of animal studies, computer modeling studies, and biomechanical theory-based literature highlighting the potential effects of high posterior tibial slope on ACL strain production, this review focuses mainly on observations that related to anatomical tibial variability. The studies included in this review, compose the body of literature associating unchanged posterior tibial slope to ACL injury**.**

In 1974, Moore and Harvey [86] described the tibial plateau angle, recommending to trace a line along the ATC and a line along the medial tibial plateau, the angle between these two lines being the tibial slope. They detected PTS angles between 7˚ and 22˚ (mean 14˚±3). In this technique, the variability of the tibial tuberosity might introduce inaccuracy.

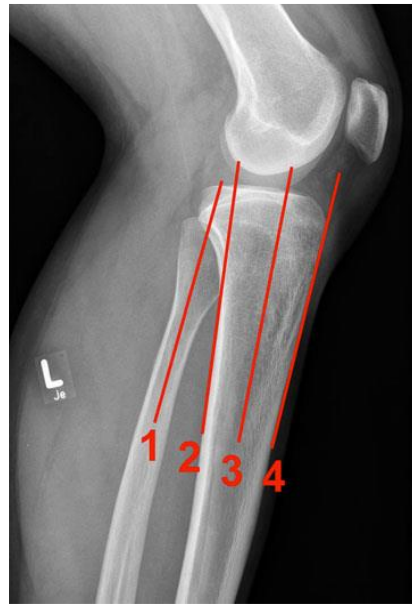


Fig. 2.5: Different anatomical axes used to measure the tibial slope. 1: proximal fibular anatomical axis (PFAA); 2: posterior tibial cortex (PTC); 3: proximal tibial anatomical axis (PTAA); 4: anterior tibial cortex (ATC) [35].

Chiu et al. [21] used also the ATC axis in determining the tibial slope on previously photographed tibias and obtained the value of 14.8˚ for medial and 11.8˚ for the lateral plateau. This study is in favor of greater tibial slope on medial than on the lateral plateau, within the ACL- intact patients**.**

Dejour et al. [26] postulated an axis to measure the PTS which is the diaphyseal axis of the tibia. Today this axis is known as PTAA which drawn as a line connecting two points equidistant between the anterior and posterior borders of the tibia, one just below the tibial tubercle and the other 10 cm below this. The advantage of this axis that it can be made on short knee radiograph films (14 x 17 in.). In their study, the mean PTS was 10˚ ± 3˚. However, diaphyseal deformity, especially bowing of the tibia, can lead to inaccuracies in this technique**.**

In 1996, Brazier et al. [14] proposed three other methods. In the first, a line is traced along the PTC and a line is traced along the medial tibial plateau, the angle between these two lines being the tibial slope. In the second, they recommend tracing a line along the PFAA and a line along the medial tibial plateau, the angle between these two lines being the tibial slope. In the third, they trace a line along the FSA and a line along the medial tibial plateau, the angle between these two lines being the tibial slope. By comparing all these techniques on 83 lateral knee radiographs, Brazier and his co-workers stated that the tibial slope values were different according to the used axis. ATC gave the higher values and PTC the smaller. The difference could be 5˚ between two methods measuring the same posterior tibial slope. The correlation with the values obtained with TDA (reference values) was stronger for PTAA and PTC.

In 2005, Çullu et al. [23] compared various methods measuring the PTS and found in the same patients higher values using the ATC method and lower values with the PFAA method.

Sonnery-Cottet et al. [104] defined the MA as the reference axis, which is drawn through the middle of the medial tibial plateau and the center of the talus **(Fig. 2.6)**.

Fig. 2.6: Tibial slope measurement based on the mechanical axis of the tibia. The mechanical axis is defined as the line connecting the midpoint of the tibial plateau and the tibial plafond [35].

The mechanical axis has also been recommended by many other authors as more representative of the true tibial slope. Using the MA, Genin et al. [40] measure PTS between 0˚ and 18˚, Julliard et al. [63] found an average value of 7˚, Yoo et al. [120] obtained PTS of 10.6˚ (range 1.9˚–19.6˚)**.** However, a larger inter-individual variability (- 0.2˚to 15˚) for the PTS has been documented in the majority of the above-mentioned studies.

Using the sagittal MA as a reference, Yoo and his co-workers compared the data of PTS obtained from 5 clinically relevant anatomical axes. These anatomical references were: ATC, PTAA, PTC, FSA, and newly created axis, which is the central anatomical axis (CAA). The study involved Korean female patients undergoing TKA for advanced osteoarthritis [120].
The degree of posterior slope varied widely among the patients. The range of the PTS was wide in all 5 anatomical references (minimum 18.2° in the ATC and maximum 20.6° in the FSA).
The mean posterior slope was 13.8° with ATC, 10.8° with PTAA, 12.9° with CAA, 7.8° with PTC, and 9.5° with the FSA. All differences by the reference axis were statistically significant.

Their results demonstrated that the maximum difference in the mean value was between the ATC and the PTC (6°) while the PTAA had the smallest divergence of the mechanical axis (0.2˚).

In a similar study, Faschingbauer et al. [32] compared the MA to the CAA (similar to that of Yoo) but they selected the points at 6 and 16 cm of the tibial shaft, and they found it to be the second best choice among axes analyzed and still introduced an error of 1.5˚ on average. However, according to the authors, there was still a significant difference between PTS measurement results if 20 cm of the tibia was used for the measurements.

Many other papers suggested the use of tibial shaft or diaphyseal axis (TDA), this axis can be calculated by dividing the overall tibial length into four equal parts on a lateral whole leg radiograph [2]. The TDA then defined as a line connecting the midpoints on the tibial shaft, which were the end of first and third parts of the tibial shaft **(fig. 2.7)**.

Fig. 2.7: Illustration shows the method of calculation the TDA on the tibial shaft.

However, the error of measurement by TDA can exceed 5°. Additionally, only the PTAA and the PTC were found not to be influenced by age, sex, patient height or weight [2, 14].

Similarly, Han et al. [46] found that tibial slope angles with respect to the MA and other anatomical axes are significantly correlated, which is in accordance with previous studies [14, 120]. Even though according to their results, TDA is the closest to the MA, its use as a practical guideline is limited. This is because surgeons cannot identify the TDA during TKA and intramedullary guides cannot reproduce this axis exactly [29], and therefore, PTAA or PTC might be substituted for MA.

There are some other studies gave important findings regarding the possible effect of the PTS on the ACL injury, but there were no sufficient details on the PTS measurement methodology.

In the analyses of Japanese 30 normal and 30 osteoarthritic varus knees using magnetic resonance imaging, Matsuda et al. [80] found that the mean MTS was 10.7° in the normal knees and 9.9° in the varus knees, of which difference was not statistically significant. In their measurements, the reference was defined as the line through two bisection points on the tibial shaft on the magnetic resonance image, but the exact site taken to identify the points was not presented.
Consequently, Kuwano et al. [68] using CT in the study of 50 Japanese knees with osteoarthritis examined before high tibial osteotomy, reported that the mean MTS was 9.0°. Their reference to measure the posterior slope was defined as the longitudinal axis of the tibial shaft. Their illustration suggested the longitudinal axis of the proximal tibia, but no detailed information was provided.

From all these previous studies, we can conclude that the different axes used In the literature are not parallel, and the values of the tibial slope within one tibia differ depending on the axis used. It can be said that the PTAA is one of the most reliable used axes which can be determined in an isolated tibia, on an X-ray image and a large MRI. Using the PTAA in healthy knees, we found that the mean MTS and LTS of the included studies are 8.4˚ and 6.3˚ respectively, which is coinciding with the previous analysis that claimed that PTS values of 7˚ to 13˚ have been considered to be physiological [12, 26].

2.4.6. METHODS OF CALCULATING THE PTAA

Three methods were found in the literature to measure the PTAA on the central axis MR image.

The proposed MRI methods for measuring the PTAA are the midpoint method, the circle method and the full tibia method **(Fig. 2.8)**, The LTS was defined as the angle between the lateral tibial plateau line and a line perpendicular to the PTAA **(Fig. 2.9)**. Each of these methods will be described in details.

2.4.6.1. The midpoint method

This method was developed by Hashemi et al. [47, 48]. It involved drawing two lines (5 cm apart) that connected the anterior and posterior cortices of the tibial shaft **(Fig. 2.8a)**. The midpoints of these two lines were connected, defining the PTAA. The measurement can be performed at three locations on the proximal tibia, with the most distal anteroposterior lines located 20 cm, and 15 cm from the knee joint line. This method can be performed easily on the routine sagittal MRI images.

However, due to the concave shape of the posterior tibial cortex, the midpoint method could be affected by the length of proximal tibia within the MR image, as well as the difference between the proximal and distal anteroposterior lines [73]. The longitudinal reference axis on the tibial bone has been described by two points approximately 4 to 5 cm apart in the middle of the sagittal orientation of the bone and the description of landmarks is insufficient. It's believed that 1 cm distance between these two points and imprecise definition of cortical landmarks (inner or outer cortical border) expose this axis to great variation. Also, the joint position on the MR image window was not defined. With a differently imaged length of the tibia, the reference points vary regarding the bone [56, 57].

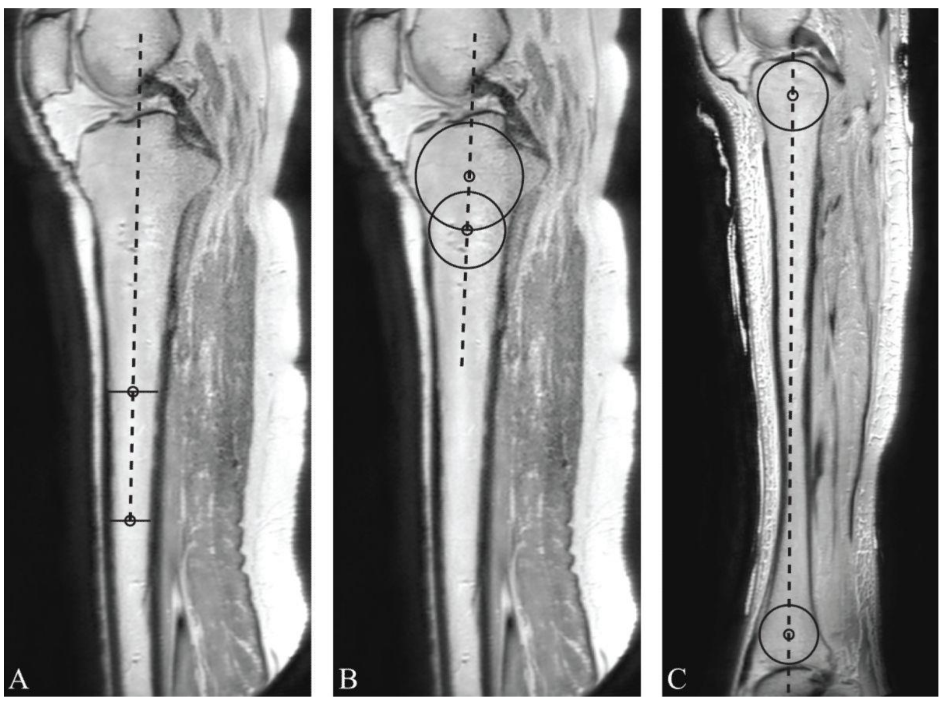


Fig. 2.8: The tibial longitudinal axis (dashed lines) was defined using (a) the midpoint method (distal line: 15 cm), (b) the circle method, and (c) the full tibia method [73].

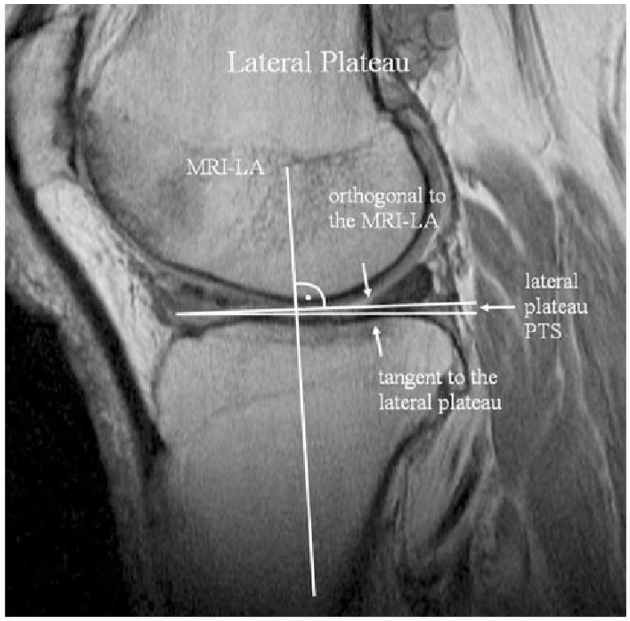


Fig. 2.9: LTS is measured at the center of articulation on the lateral tibial plateau. PTAA is superimposed on the image. The PTS is the angle between a line fit to the subchondral bone line and a line perpendicular to the tibial longitudinal axis (MRI-LA) [57].

2.4.6.2. The circle method

This method was firstly introduced by Hudek et al. [57], it involved drawing two circles within the proximal tibia **(Fig. 2.8b)**. The proximal circle was fitted within the proximal, anterior, and posterior cortical borders. The center of the distal circle was positioned on the perimeter of the proximal circle and was fitted within the anterior and posterior cortices.

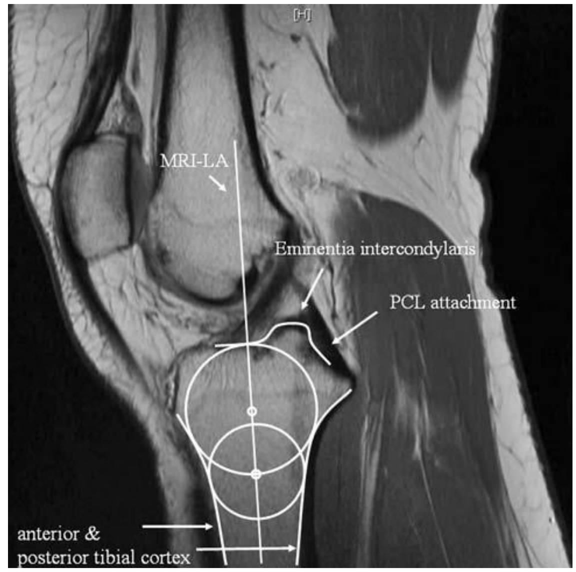
On MRI, the measurement can be performed in three steps:

A- Choosing the central sagittal image: in which the tibial attachment of the posterior cruciate ligament PCL (1), the intercondylar eminence (2), and the anterior and posterior tibial cortices appeared in a concave shape (3) **(Fig. 2.10)**.

B- Positioning of one cranial and one caudal circle in the tibial head. The circles were applied by computer software which provided an infinite number of diameters and free positioning. All measurements were positioned as an overlay and remained in a fixed position on the complete image series **(Fig. 2.10)**. The cranial circle had to touch the anterior, posterior, and cranial tibial cortical borders, and the caudal circle had to touch the anterior and posterior cortical borders.

C- A line connecting the center of these two circles defined the PTAA.

Fig. 2.10: The central slice on MRI is shown with integrated circles, which represents the basis for assessing the longitudinal axis (MRI longitudinal axis). PCL = posterior cruciate ligament [57].



Using this axis presumed that the PTS could be determined on conventional MRI at least as reproducibly as on a true lateral radiograph using a standard definition of the longitudinal axis. According to the authors, the limiting factor of this method is that the section planes on MRI must be parallel to the anatomic axis in the coronal plane. During the imaging process, this parallelism is manually approximated by the radiologist which may result in more inaccuracy [57].

2.4.6.3. The full tibia method

This method includes fitting a circle within the proximal tibia (connecting the anterior, proximal, and distal cortical borders) and the distal tibia (connecting the anterior, distal, and posterior cortical borders) **(Fig. 2.8c)**. The centers of these two circles were connected to define the full tibial anatomical axis. One can argue that, this method can't be applied to the MRI films that usually don't show the full length of the tibia.

Lipps et al. [73] performed an important study to compare these three methods in a group of cadavers by using MRI. Their results showed that the LTS measurements using the midpoint method, with 10 cm or 15 cm of proximal tibia closely resemble LTS measurements using the full tibia and the reliability of the midpoint method depends on the length of proximal tibia used.

Moreover, the midpoint method is affected by the length of proximal tibia within the MR image due to the concave shape of the posterior tibial cortex. While there was no significant difference between 10 cm and 15 cm of the proximal tibia using the midpoint method, their data demonstrated more variability between these measurements and 20 cm of proximal tibia **(Fig. 2.11)** [73]**.**

The authors explained the presence of negative values with the midpoint method at 10 cm and 15 cm of the proximal tibia in some knees, may be due to the tibial tuberosity that shifting the PTAA more anteriorly **(Fig. 2.12)**. This obstacle did not affect LTS measurements with the circle method because the distal circle lies proximal to the tibial tuberosity.

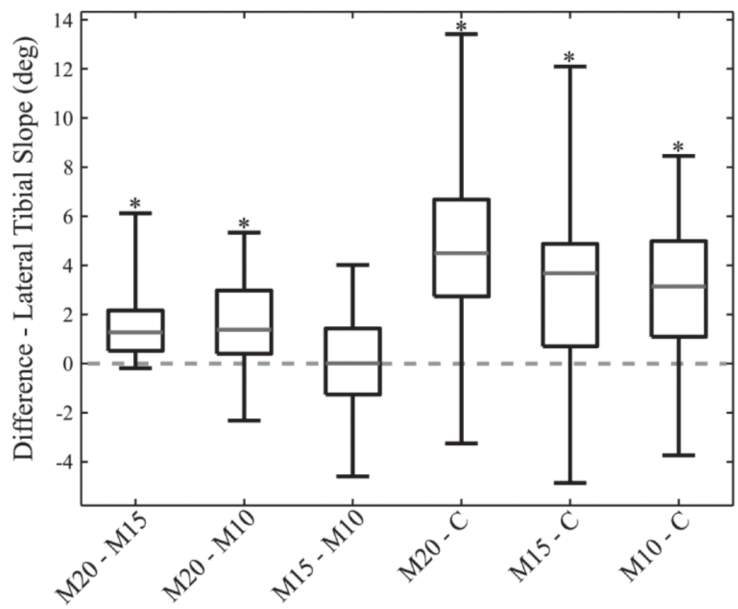
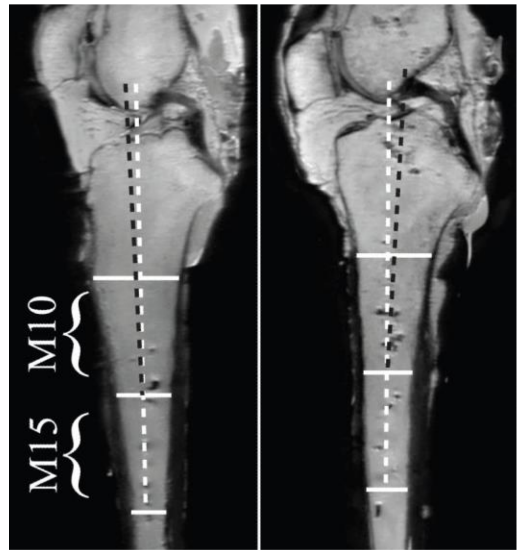


Fig. 2.11: The box plots compare the difference in LTS measurements using the circle method (C) and the midpoint method with 20 cm (M20), 15 cm (M15), and 10 cm (M10) of the proximal tibia. The asterisk denotes a significant difference between 10 cm and 15 cm of the proximal tibia, and the measurements of 20 cm of the proximal tibia [73].

It can also be say an average LTS of 8.4˚ measured with the midpoint method is equivalent to an LTS of 5.3˚ using the circle method, based on the mean difference (3.1˚) between the 15 cm midpoint method and the circle method [48].

Fig. 2.12: The tibial tuberosity can affect PTS measurements by the midpoint method. This anatomical projection will affect the ability to perform the M10 measurement, as it will shift the tibial PTAA (white dashed line) more anteriorly [73].



They concluded that the midpoint method, particularly with 15 cm or 10 cm of the proximal tibia, is a better representation of the full tibial anatomical axis than do the circle method **(Fig. 2.13)**. On the other hand, the circle method also showed the best inter- and intra-observer reliability.

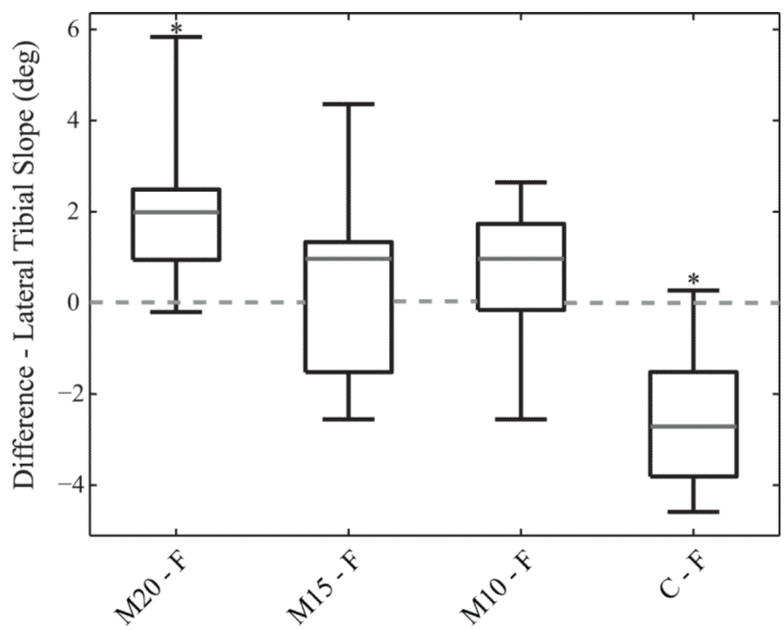


Fig. 2.13: Box plots of the differences in lateral tibial slope measured by the full-tibia method (F) method with methods utilizing only the proximal tibia: the circle method (C) and the midpoint method (M20, M15, and M10). the asterisk denotes a significant difference [73].

2.4.7. DIFFERENT MODALITIES USED FOR PTS MEASUREMENT

We are well aware that previous studies have validated different imaging methods for measuring the tibial slope. No significant difference exists between radiographs, computed tomography, and MRI. However, recent work has focused on MRI [9, 48, 56, 57, 73, 103, 106, 110].

2.4.7.1. RADIOGRAPHY

The radiological protocols are a valuable, low-cost, accessible tool which helps to collect varied and fundamental information concerning bone morphology.

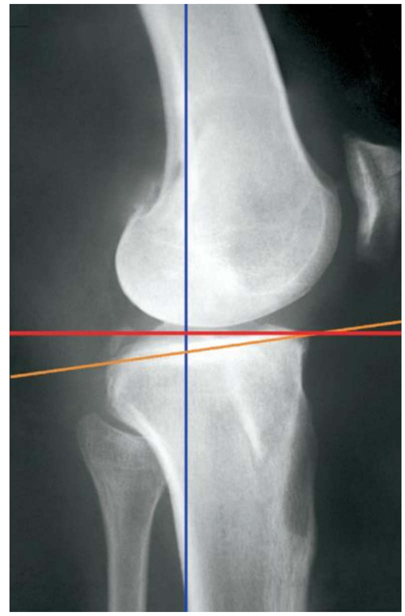
The procedure that was used to determine the tibial slope was based on the radiographic techniques developed by Genin in 1993 [40].

Morphological characteristics identified in conventional X-ray protocols can provide an inexpensive, effective, and feasible tool to identify individuals at higher risk for ACL lesion [94].

Generally, a true lateral radiograph must be obtained to derive an accurate and reliable measurement of the tibial slope **(Fig. 2.14)**. Standard radiological evaluation of the tibia slope should include standing lateral view in full extension with the femoral condyles exactly superimposed and 30˚ of flexion [14, 40, 63, 94].

The accuracy of tibial slope measurements using these strict criteria has been reported between 1° and 4° [62]. The measurements based on lateral radiographs have shown the tibial slope of the knee to average 10 ± 3° [26, 40].

Fig. 2.14: Using a true lateral radiograph of the knee, the femoral condyles are superimposed. It must be taken in full extension.



Various models for PTS measurement on conventional lateral radiographs have been described, [26, 40, 86, 93]. However, it is still imprecise. As a consequence of superimposition, the lateral tibial plateau is difficult to identify, and the separate assessment of the two tibial plateaus is not reliably possible on lateral radiograph [61, 63].

It has been noted that reported tibial slope values for healthy knees vary greatly among our recruited studies. Kessler et al. reported in their study, measurement errors of more than 5° using conventional radiographs. They established an error of measurement of 14° with the rotation of the tibia. By introducing the use of computed tomography, the measurement error is decreased to less than 3° [65].

By using lateral radiographs, Lee et al. found that the measurement of the posterior slope was reproducible and reliable, and demonstrated significant increases in tibial slope measurements within the same population when lateral radiographs were compared with sagittal MRI. These differences were more significant on the lateral side [69].

Accordingly, Han et al. stated that tibial slopes obtained from conventional plain X-rays are of limited value because they have poor reproducibility, caused by tibial rotation in lateral view [46].

Characterizing the tibial plateau surface with a single slope measurement represents a rough calculation of its real three dimensions, and the biomechanical effect of the tibial slope likely to be more complex than previously appreciated [35, 94].

Numerous authors affirmed the need for measurement of PTS in both plateaus as a result of large differences observed between the two tibial compartments [61, 80, 106, 120, 65]. Such differences may be involved in the pathomechanics of ACL injury.

One can argue that the lateral radiograph measurement is based on one image, while on MRI, several images should be assessed in consecutive steps. As a result, the reproducibility was to relatively better on a radiograph than with MRI. Obtaining lateral radiographs of the entire lower limb allows better measurement of the PTS while it's difficult to capture the entire tibia in one MRI film.

Furthermore, The cost and time consumption of a routine knee MRI is approximately five times greater than for a lateral radiograph, and MRI is not the modality of choice for routine knee arthroplasties or tibial osteotomies [57].

2.4.7.2. COMPUTED TOMOGRAPHY (CT)

As mentioned previously, tibial slopes obtained from conventional plain X-rays of limited value because they have poor reproducibility, caused by tibial rotation in lateral view [76]. In contrast, measurements based on three-dimensional reconstructed computed tomography (3D CT) images are substantially more accurate because variations in tibial slopes are smaller [65]. Moreover, using this modality, CT images can be rotated without restraint after reconstruction, and 3D axes can be determined with excellent reproducibility and reliability whereas the PTS measurement errors decrease to less than 3° [46].

Many studies used the CT scan to measure PTS, Kuwano et al. determined the PTS on both condyles by means of a 3D CT, with an image capturing 150 mm of the proximal end of the tibia. The mean MTS and LTS were 9.0° and 8.1°, respectively. They claimed that full extension of the knee joints is not easy. Therefore, it is difficult to obtain the correct constant anteroposterior view of the knee joint by radiograph. Furthermore, the 3D CT images can be rotated without restraint, and the correct and constant three-dimensional axes can be determined and maintained [68].

Akamatsu et al. assessed tibial slope measurements on the knee, whole leg radiographs, and 3D CT in 50 patients with knee osteoarthritis. By comparing these techniques, the reproducibility and reliability of MTS and LTS on CT were superior to those on the whole leg radiographs which in turn had better reproducibility and reliability than those on knee radiographs [2].

In another large CT study, Nunley et co-workers measured the PTS in patients undergoing Unicompartmental knee arthroplasty (UKA) [90]. The study was performed on more than two thousand CT. After the acquisition of the CT scan, they designed a 3D model for the knee joint **(Fig. 2.15)**.

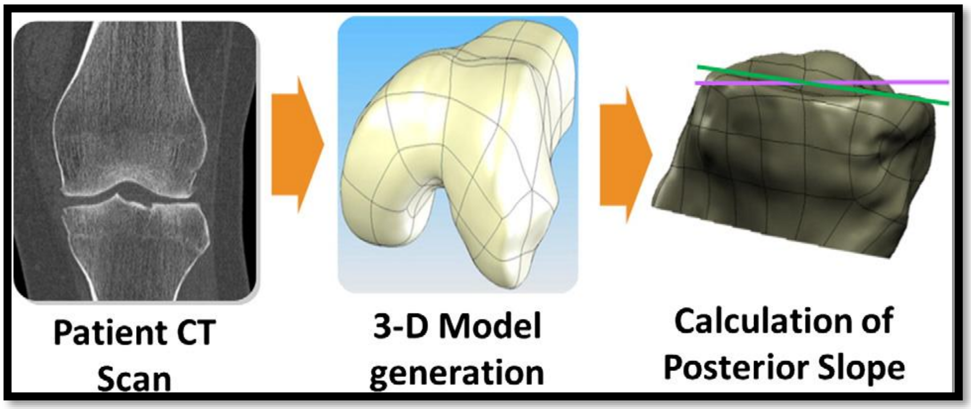


Fig. 2.15: Overview of the process of developing a 3-D model and calculation of the PTS based on a preoperative CT scan [90].

On this 3D model, the PTS was defined as the angle between a line tangent to the highest points of the anterior and posterior cortices of the tibial compartment and the perpendicular plane to the MA **(Fig. 2.16)**.

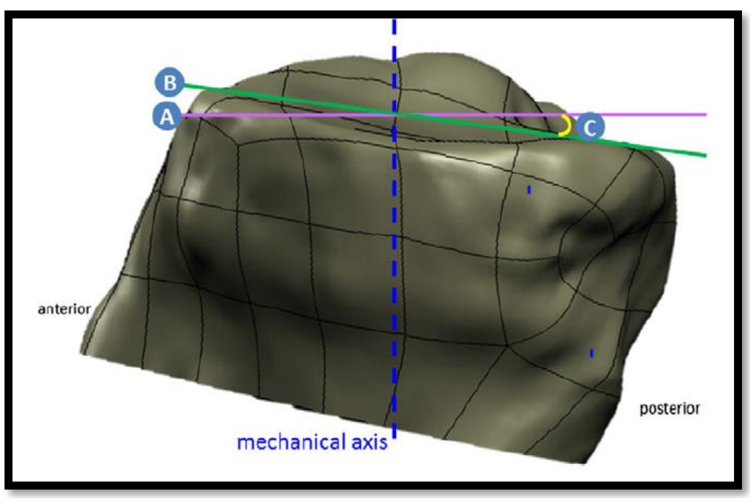


Fig. 2.16: Sagittal view of a 3D model of the knee. The angle between the patient's natural slope (green line B) and the perpendicular plane (purple line A) defined the PTS of the compartment [90].

They demonstrated a marked variability of the PTS with 44% of medial plateaus and 60% of lateral plateaus having greater than 7° of the anatomical PTS, with a range of 26.4° and 22.5° in the medial and lateral compartments, respectively.

These findings may reflect that tibial slope measurement using 3D CT required time and specialized software [2]. Therefore, measurements of the MTS using whole leg radiographs were more reproducible and reliable and could be an alternative to CT in clinical practice.

2.4.7.3. MAGNETIC RESONANCE IMAGING

Although lateral radiographs are better to assess the MTS, they are inadequate for reliable and separate PTS measurement. Therefore, it is recommended to use conventional MRI scans of the knee, because they allow a simple assessment of each plateau separately and afford the possibility to assess reliably the soft tissue slope [56].

One of the greatest strengths of using MRI for this application is the ability to visualize the surface geometry of the articular cartilage, which represents the functional point of tibiofemoral joint, in addition to the possibility of individual measurement of the tibial slope in both compartments and their associated tissue structures, a strong case can be made for preference to MRI over radiographs [7, 78].

The simple demarcation between medial and lateral plateaus on MRI is quite important for research questions and may be introduced to knee intervention if operative methods account for the differences in the anatomy of two tibial plateaus [57].

In our review, 35% of the included studies (n=16) were MRI-based, and most of them used the midpoint method and/or the circle method for measuring the tibial slope.

Some studies used Hashemi method and reported the most similar results [9, 47, 110]. On the other hand, Khan et al. [66] choosing the central sagittal image and midarticulating sagittal images of the medial and lateral tibial plateau, as described by Hashemi et al. [47] and then drawing the PTAA using the method of Hudek et al. [57] based on their reports, this combined method provided simple measurement with greater reliability.

Matsuda et al. [80] described the PTS on MRI with an average value of 10.7˚ (range, 5˚–15.5˚) for the medial plateau and 7.2˚ (range, 0˚–14.5˚) for the lateral plateau in ACL patients by scanning the entire tibia from the tibial plateau to the ankle. However, such a method is impractical for routine clinical imaging.

An MRI scan of the full length of the tibia can produce plane distortions which may lead to a twisted appearance of long bones, thereby compromising the correct assessment of the longitudinal tibial axis [57].

Several studies have compared the measurement taken by MRI to those taken by radiography, Lee et al. [69] demonstrated significant increases in PTS measurements within the same population when lateral radiographs were compared with sagittal plane MRI. These differences were more significant on the lateral side.

Hudek et al. [57] found that the average MTS on MRI was 3.4˚ smaller than on a true lateral radiograph in the same knee. They noted typical interobserver and intraobserver errors of ±1.4° and ±1.2° respectively, while another study has demonstrated much larger errors using radiographs [65]. However, on conventional MRI scans of the knee, only the proximal tibia is observed and determination of the full longitudinal axis is not possible.

Simon et al. [103] have modified Hashemi method based on a 3D reconstruction of the tibial geometry and subsequent measurement of the tibial slope.

By using AMIRA software, according to the authors, the outline of the tibia in each axial slice was segmented and the blow tool is designed to allow interactive determination of the boundaries where a large image gradient exists. It expands from a seed point across homogeneous gray values as the mouse is dragged, but stops when it senses a large gradient, corresponding to the boundaries of the bones. Subsequent to segmentation of the bones, the original MRIs were used as a guide to identify the medial and lateral subchondral bone surfaces **(Fig. 2.17)**.

Once the tibial plateaus were determined, the principal axes of each subchondral surface were calculated from the eigenvectors of the set of surface points to choose an objective best-fit plane to the data points.

The long axis of each tibia was determined by automated calculation of the centroid of the bone from several transverse slices. The line intersection of this plane to the sagittal plane was calculated and finally, the tibial plateau slope for each tibiofemoral compartment was calculated as the angle of this intersection line relative to the long axis of the tibia.

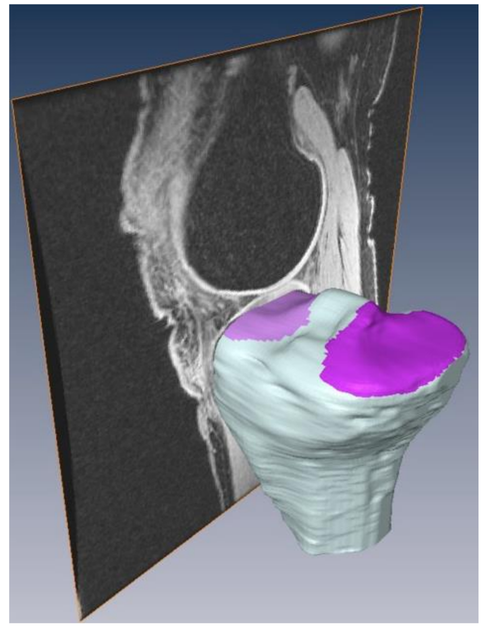


Fig. 2.17: Image of the segmented tibia with the marked Medial and lateral tibial plateaus (purple). The sagittal MRI slices were used to identify the subchondral bone [103].

This advanced method to help avoid the potential subjectivity and inaccuracy due to improper choice of the sagittal slice, incorrectly drawing the lines for the slope or long axis, or inability to ensure that the knee was in full extension during scanning [103].

Ideally, to define the posterior tibial slope from sagittal plane MRI, you must first determine the tibial anatomical axis. Next, the proper anatomical slice that best characterizes the tibiofemoral articulation on the side of the tibia of interest should be chosen and the tibial axis superimposed onto the image. Finally, the line defining the medial or lateral articular surface of the tibia must be defined. The PTS angle is defined as the angle between this articular surface and a line perpendicular to the tibial axis [26, 58, 47, 57].

In addition to potential errors at each of the above-mentioned steps is the potential for misalignment of the patient within the magnetic resonance device during imaging. Careful steps should be taken to align the patient such that a true anatomical sagittal view is obtained.

This may include standardization of knee flexion angle and foot alignment, palpation of anatomic landmarks at the proximal and distal tibia during positioning to adjust alignment, and immobilization of hip internal/external rotation during positioning and acquisition.

When possible, computerized 3D reconstructions of the tibiofemoral geometry and articular surfaces should be used to ensure the greatest constancy in slice alignment and anatomical position for the proper analysis. Given the sensitivity required of this measurement for utility as a risk-identifying tool, clinical recommendations for each of these steps that can be universally employed with high repeatability should be the next step in the advancement of this line of research [119].

Nowadays, besides morphological measurement, it is possible to combine morphological and functional assessment of the knee joint during one single MRI or CT-based examination by means of using Porto Knee Testing Device (PKTD) [31]. In this way, one might combine the morphological study of bony parameters with evaluation of anteroposterior and rotational laxity **(Fig. 2.18)**. By combining CT with PKTD, the joint parameters concerning laxity can be simultaneously measured **(Fig. 2.19)**.

These data provide one further step in understanding the knee kinematics, but their functional implication and the way in which they might affect ACL reconstruction are not fully achieved. ACL research demands perseverance and patience [77].

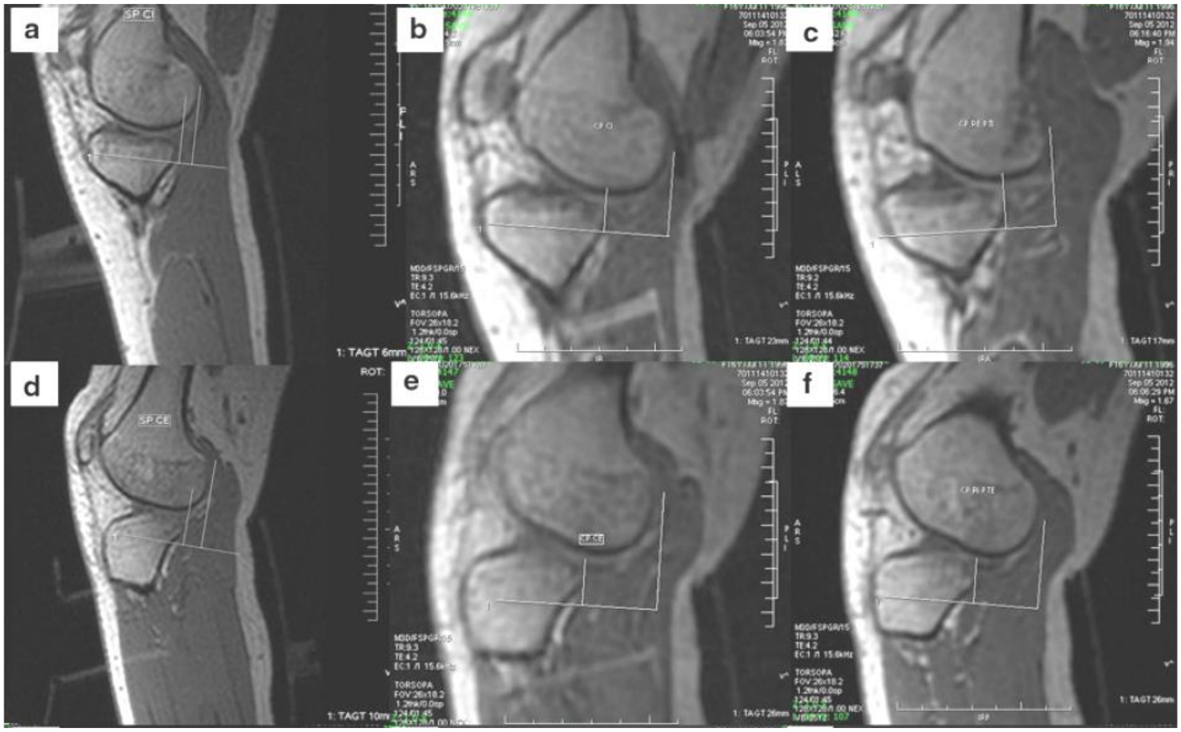


Fig. 2.18: Standard protocol evaluation with PKTD: Sagittal view with the foot in the neutral position without load application correspondent to medial (a) and lateral compartments (c). The result after load applications correspondent to medial (b) and lateral compartments (d). In this case, the differential would be 16 mm. Image correspondent to load after maximum internal foot rotation in the lateral compartment (e) and after maximum external foot rotation in the medial compartment (f) [94].

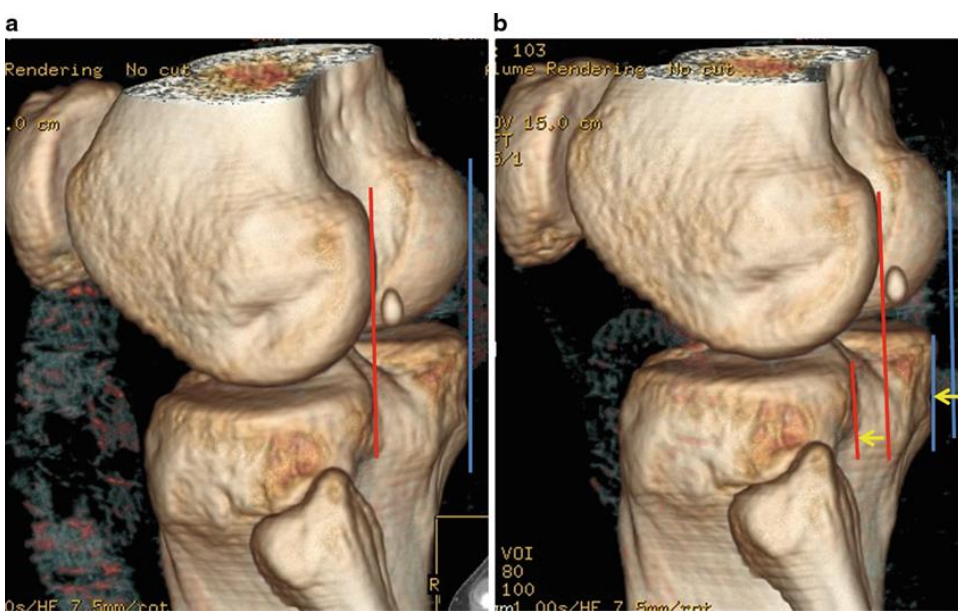


Fig. 2.19: CT 3D imaging reconstruction of PKTD examination. Initial position without load application (a). After load application notice yellow arrows representing anterior tibial displacement (b) [94].

2.4.8. TIBIAL SLOPE AT BOTH COMPARTMENTS OF THE KNEE

Recently, several authors have emphasized that characterizing the tibial plateau surface geometry with a single slope represents only an insufficient approximation of its three-dimensionality, the functional consequences of the tibial slope might be more complex [47, 81, 78, 103].

The assumption that the tibial slope is consistent is potentially misleading in clinical practice, as the MTS and LTS in an individual are not necessarily similar and the variability between individuals is high [78].

Current data on the PTS of the normal knee demonstrate a wide range of values, with a reported range of [−3° - 14.7°] for the MTS and [0° -14°] for the LTS which is consistent with previous research [47, 90]. Additionally, differences of as much as 27˚ have been reported in cadaveric studies [57].

Consequently, it remains unclear whether the risk of noncontact ACL injury could be increased in those with the increased slope in one or both compartments.
It has been reported that ACL injured patients have a greater LTS than MTS and the difference between these two slopes may influence dynamic landing knee biomechanics [73]. Hashemi et al. in their MRI study of 55 knees found that lateral compartments had steeper slopes than medial compartments [47]. Haddad et al. [45], and Hudek et al. [56] found no difference between the PTS of both compartments. However, whether significant differences exist between the PTS of the medial and lateral tibial plateaus remains controversial.

The mechanism of the relationship between a steep LTS and ACL injury may be explained as follows: Under axial loading, the lateral femoral condyle slides posteriorly along the lateral tibial plateau, resulting in a relative external rotation of the femur or relative internal rotation of the tibia [35, 103] (**Fig. 2.20**). Since the external rotation of the femur causes increased strain on the ACL a steep LTS may contribute to ACL injury [37, 79]. The sliding mechanism of the lateral femoral condyle might be enhanced by the convex shape of the lateral tibial plateau, which provides less bony stability compared to the concave medial tibial plateau [11]. Furthermore, the lateral meniscus is more mobile compared to the medial meniscus thereby allowing more movement of the lateral condyle [4].

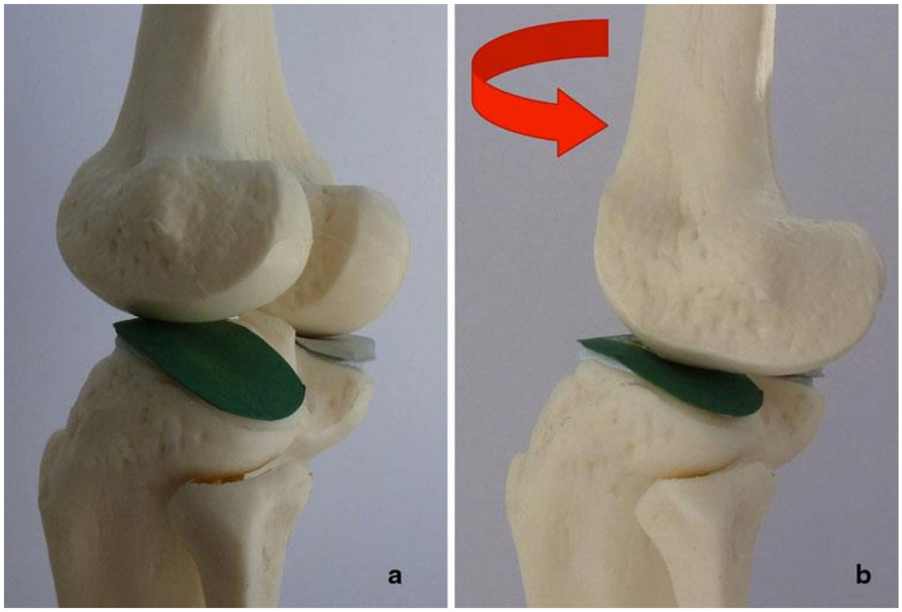


Fig. 2.20: Mechanism between a steep LTS (green plate) and increased external rotation of the femur. (a) Before axial loading (resting position). (b) Under axial loading, the lateral femoral condyle slides posteriorly along the lateral tibial plateau, resulting in an external rotation of the femur (red arrow) [35].

In contrast to the previous findings, Vyas et al. stated that there is a significantly increased MTS in teenaged subjects with open physes with ACL injuries when compared to control subjects, but there was no significant difference in LTS between the two groups. They suggested that this increase in anterior-posterior translation in the knee, caused by the increased tibial slope, may predispose the teenage population to ACL injuries [116].

This contrary between the previous studies, according to the authors, could be because the MTS has a closer approximation to the tibial insertion of the antro-medial (AM) bundle of the ligament, therefore increasing its influence on anterior-posterior translation when compared to the LTS.

2.4.9. POSTERIOR TIBIAL SLOPE DIFFERENCE BETWEEN MALE AND FEMALE

The effects of patient demographics, such as gender and age, on the tibial slope, have not been fully elucidated**.** Some authors found the correlation between the tibial slope and the ACL injury to be sex-dependent. Females with steeper tibial slope are at greater risk of noncontact ACL injury than males [43, 48, 54, 66, 110, 111]. While others found no correlation at all between the two parameters [56, 83].

In 2006, Brandon et al. performed a study on lateral radiographs to determine whether an increased PTS is associated with ACL rupture. They found that female ACL-insufficient patients had a significantly greater PTS (12.0˚) than their negative controls (8.6˚). This finding was also true for men. Moreover, Female patients didn’t have significantly greater mean PTS than male patients [13]. Similar findings achieved by Terauchi et al. who found that MTS was significantly larger in the ACL-deficient females than in the control group (10.9° and 8.2°, respectively) [110].

Correspondingly, Hashemi et al. studied the geometry of the tibial plateau in normal subjects and found that the mean MTS for the female subjects was significantly greater than that for the male subjects (5.9˚ vs. 3.7˚). Similarly, the mean LTS for females was significantly greater than that for the males (7.0˚vs. with 5.4˚) [47].
In 2010, the same authors performed another MRI study to measure the MTS, and LTS in 49 subjects with ACL injury (27 women, 22 men) and 55 control subjects (33 women, 22 men). Compared with female control subjects, women with ACL injury had greater LTS but not MTS. Uninjured women had significantly greater MTS and LTS compared with uninjured men [48].
In contrast to the previous studies, Bisson and Gurske-DePerio found a significantly increased LTS in men with ACL injury compared to women [9].

Many possible risk factors have been suggested for this observation. Apart from the steeper lateral tibial slopes, Charlton et al. [19] found that the volume of the femoral intercondylar notch was statistically smaller in women compared with men; this difference was primarily related to height. A similar relationship was found for ACL volume [3, 18].

Biomechanically, In a cadaver study of 10 males and 10 matched females, Lipps et al. [72] found a higher peak ACL strain in female knees than male knees under simulated pivot-landing test conditions.

All of these factors have been hypothesized to account for relative increased ACL injury risk for females as compared to males. However, a major limitation of the current literature is that these previous studies only compared females to males, and are unable to make general conclusions about other intrinsic risk factors that put anyone at an increased risk of injuring their ACL.

Another weakness of previous studies is the use of subjective methods, using landmarks that are difficult to justify clinically and duplicate. Finally, previous works have tended to examine individual variables from a single data set, thus limiting their applications and conclusions.

2.4.10. ROLE OF MENISCI

The relationship between tibial slope and ACL rupture remains controversial despite the considerable number of published studies. The lack of agreement could be attributed to the definition of the tibial slope as merely a bony configuration of the tibial plateau, despite the likelihood that the slope generated by the soft tissues, such as cartilage and menisci, forms a more functional interaction with the femoral articular surface [56]. As the posterior horns of the menisci are usually thicker than the anterior horns, the posteriorly oriented bony tibial slope is ultimately reduced by the menisci [13, 35, 70].

The term meniscal slope (MS) has been introduced by Jenny et al. [61]. An analogous to the PTS, the MS was defined as the angle between a tangent line between the superior meniscosynovial border of the respective meniscus and the longitudinal axis of the tibia.

These authors demonstrated a mean difference between the bony tibial slope and the meniscal slope of 6˚, with the meniscal slope being almost perpendicular to the proximal tibial anatomical axis.

Recently, assessment of the MS has received considerable interest [22, 56, 69, 77].

Hudek et al. [56] performed a study to assess whether the PTS and MS are associated with the risk of noncontact ACL injury by reviewing the MRI of 55 ACL injured patients with contact menisci and the same number of a control group **(Fig. 2.21)**. They observed a greater lateral MS in the patients with ACL injuries, which leads to the suggestion that a greater lateral MS is associated with a greater risk for noncontact ACL injury.

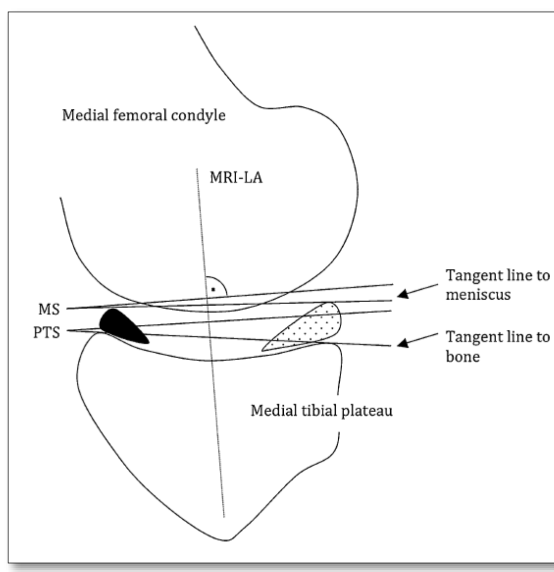


Fig. 2.21: The assessment of the PTS and MS on MRI. The diagram shows the contours of a sagittal MR image at the medio-lateral center of the medial plateau. A tangent line is drawn to the most superior anterior and posterior cortex edges of the medial bony plateau. Accordingly, the superior anterior and posterior meniscal borders mark the MS [56].

In 2013, Lustig et al. examined MRI sagittal images from 101 patients presenting with complaints of anterior knee pain and calculated both the bony tibial slope and subsequently the slopes of both menisci. From their results, they concluded that the soft tissue slope can be measured reliably using an MRI-based method and that the knee menisci significantly reduce the tibial slope towards the horizontal plane. Furthermore, the soft tissue slope is more horizontal in the lateral compartment of the knee compared to the medial one [78].
This parameter might be of particular interest for future studies because the menisci are important contributors to sagittal and rotational stability [70, 88]. Other studies observed a significantly lower depth of the concavity of the medial tibial plateau in ACL-injured subjects compared to uninjured controls A shallow medial plateau may be associated with low resistance to displacement of the tibia relative to the femur because of less joint congruity, thereby reinforcing the impact of the bony or soft tissue tibial slopes [48, 66].

There are some potential limitations to this review. First, some studies may have been missed from the current literature search. However, the employment of three databases and the thorough review of interesting references, including a full-text reading of the most important references, and the careful double-check of cross studies minimized this risk. Second, many studies had a low number of cases with the absence of significance in the principal comparisons. Third, several studies did not reveal detailed information of the reference used. Fourth, non-prospective studies may have a high risk of bias, especially for those modifiable factors. It is very important that adequate prospective cohort studies are designed to assure confident data analysis and conclusions.

2.5. CONCLUSIONS

The findings of the analyzed studies confirm our assumption that different methods defining the reference tibial axis will produce different tibial slope measurements. the lack of agreement between measurement methods in clinical research studies resulted in variations in the tibial slope of the proximal tibia up to 12° for both medial and lateral tibial slope in ACL-injury as well as normal knees.

The recruited studies in this review are the best available evidence to date for the evaluation of the PTS. However, we see an improving trend in reporting, as the most recent publications were generally presented as having a lower risk of bias.

Some of the inconsistencies in these reports may be attributed to the use of different methodologies. However, several studies had used the same techniques but with varying results.

These subtle differences between the tibial slope studies are further amplified by variation in the selection of the samples. To date, no uniform definition exists for non-contact ACL insufficiency, making patient selection difficult. Thus, inconsistent results might also be a consequence of different patient selection and inclusion patterns.

Among the modalities used for PTS measurement, the greatest advantages of using MRI for this application is the ability to visualize the surface geometry of the articular cartilage, which represents the functional point of tibiofemoral joint, in addition to the possibility of individual measurement of the tibial slope in both compartments and their associated tissue structures, a strong case can be made for preference to MRI over radiographs.

No consensus has been reached regarding the choice of the reference axis for the tibial slope measurements. With respect to the current literature, the most representing anatomical reference for the sagittal MA was the PTAA. The PTAA can be drawn in a relatively short radiograph (14 ×17 in), which makes it possible to estimate the sagittal alignment with radiographs of the routine follow-ups. Moreover, The PTAA method of the tibial slope measurement is used routinely for different surgical procedures like high tibial osteotomy [89].

It appears that the midpoint method specifically, is a better representation of the full tibial anatomical axis. When applying this method, the clinical measurements of LTS should employ a standardized length of 150 mm of proximal tibia below the joint gap of the knee [14, 23].

The adult MR scans should be obtained with a knee coil to adequately determine the PTAA and to avoid the undesired effect of the bony projection like the tibial tuberosity [35].

The circle method measurement of the PTAA will result in an LTS measurement that is significantly smaller than that with the midpoint method. Despite this finding, the circle method is still an excellent choice for measuring LTS when comparing knee coil MR images with variable lengths of the proximal tibia.

The lack of a consistently employed gold-standard method for the measurement of the tibial slope also impedes the interpretation of the existing literature in defining a threshold for the PTS that demonstrates a distinction between controls and ACL-injured patients. Across studies, there is an overwhelming intersection of values for the tibial slope that is reportedly associated with uninjured subjects and those associated with ACL injury. All of the authors reported a high SD and range. Given that wide average difference in tibial slope between controls and ACL-injured.

The incongruity between these studies might attribute also to the etiology of non-contact ACL injuries that is most likely multifactorial, other anatomical variations, the dynamic behavior of the tibial slope might be influenced by other surface parameters such as a narrow intercondylar notch, smaller ACL volume and steep lateral MS. Therefore, it seems difficult to investigate one risk factor independently, and future research should consider these anatomical variations together.

Overall, we performed an expanded review of studies reporting PTS as a risk factor for ACL injury. Most of the studies indicated that there is a potential relationship between ACL injury and posterior tibial slope. Their data show that each of the measurement methods currently employed has shortcomings in their reliability. Highly variable evidence for the role of PTS and other anatomical measures in injury risk assessment makes interpretation of the current literature difficult. However, the method defined by Hashemi et al. is the most frequently used and shows the moderate repeatability across studies [47]. This should be the preferred methodology until a significantly more reliable and standardized protocol is defined and validated in the literature. Such a method should rigidly define the tibial slope measurement process from initial imaging parameters to actual tibial slope measurement. In addition to that, this method should imperatively provide significantly greater inter-rater reliability.

Future efforts should also be made to standardize the measurement method of the PTS, including tibial axis, sides of the plateau, and imaging modalities in order to characterize tibial plateau slope and provide a more objective and reliable assessment of risk factors after ACL injury, so as to make it easier to compare studies. Such methodologies will also enhance the objectivity of tibial slope as a factor in the assessment of post-injury stability and long-term sequelae.

To make the measurement of the tibial slope more reliable, these future studies should use a prospective recruitment of consecutive noncontact ACL-injured patients with double-blinded image analysis.

Dynamic MRI with PKTD has brought novel insights to more detailed anatomic and functional evaluation. More important than a single research line, it would be necessary to combine all up-to-date insights and modern knowledge in a single and practical screening method. Investigators should carefully consider the question that they are trying to answer when choosing the imaging modality and the measurement method they wish to use.

The goal of the line of future research relating PTS to ACL injury risk should be to establish not only the extent of the role of the tibial slope in injury risk but also the extent to which that risk can be decreased by prophylactic interventions.

Subjects with an increased tibial slope who are participating in high-risk activities such as soccer should perhaps consider prophylactic precautions. This could include education on the increased risk for ACL rupture, and injury prevention such as neuromuscular training should be advised. If future ACL injury prevention program involves morphological screening, it is important to recognize that PTS measurements are method-dependent.

2.5.1. Compliance with ethical standards

The authors declare that there are no conflicts of interest.

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Chapter 3

MRI CASE-CONTROL STUDY

PROXIMAL TIBIAL BONY AND MENISCAL SLOPES ARE HIGHER IN ACL INJURED SUBJECTS THAN CONTROLS

A Comparative MRI Study

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ABSTRACT

Purpose: Increased tibial slope is reported as a risk factor of non-contact anterior cruciate ligament (ACL) injury, but the effect of the soft tissues on slope remains unclear.

The primary aims of this study were to compare the tibial bony and soft tissue slopes between patients with and without ACL injury and to investigate the relationship between the meniscal slopes (MS) and the tibial bony slope.

Our hypothesis was that the menisci would correct the inclination of the bony tibial slope towards the horizontal.

Methods: Using magnetic resonance imaging (MRI), the lateral and medial tibial slopes (LTS, MTS) and lateral and medial meniscal slopes (LMS, MMS) were compared in 100 patients with isolated ACL injury and a control group of 100 patients with patello-femoral pain and an intact ACL.

Results: Repeated-measures analysis of variance showed good inter- and intra-observer reliability for both bony and soft tissue slopes (ICC (0.88–0.93) and (0.78–0.91) for intra- and inter-observer reliability, respectively).

The LTS and MTS were significantly greater in the ACL injury group (10.4 ± 3.1 and 9.4 ± 3.3) than in the control group (7.3 ± 3.4 and 7.0 ± 3.7). Similarly, the LMS and MMS were significantly greater in the ACL injury group (4.7 ± 4.7 and 6.0 ± 3.4) than the control group (0.9 ± 4.8 and 3.7 ± 3.6). In both groups, the lateral bony tibial slope was greater than the medial bony tibial slope, but the medial soft tissue slope was greater than the lateral soft tissue slope.

Conclusion: Increased tibial slopes, both bony and meniscal, are risk factors for ACL injury. As the meniscus tends to correct the observed slope towards the horizontal, loss of the posterior meniscus may potentiate this effect by increasing the functional slope.

Level of evidence III.

Keywords Knee · Tibial slope · Anterior cruciate ligament injury · Meniscus · MRI

RÉSUMÉ

La pente tibiale augmentée est rapportée comme un facteur de risque de la blessure non-contact du ligament croisé antérieur (LCA), mais l'effet des tissus mous sur la pente n'est pas claire.

Les buts principaux de cette étude étaient de comparer la pente de tissu mol et la pente tibiale entre des patients avec et sans blessure du LCA et de examiner la relation entre la pente méniscale (MS) et la pente tibiale.

Notre hypothèse était que le ménisque corrigerait l'inclination de la pente tibiale osseuse vers l'horizontale.

En utilisant l'imagerie par résonance magnétique (IRM), les pentes tibiales interne et externe (LTS, MTS) et les pentes méniscales interne et externe (LMS, les MMS) ont été comparées dans 100 patients avec des blessures isolées aux LCA et un groupe contrôle de 100 patients avec la douleur patello-fémorale et un intact LCA.

Analyse des variations de mesures répétées a montré de bonne réalisabilités inter-observateurs et intra-observateur (ICC (0.88–0.93) et (0.78–0.91) pour réalisabilités intra-observateur et inter-observateurs, respectivement).
Les LTS et MTS étaient significativement plus grands dans le groupe de blessure au LCA (10.4 ± 3.1 et 9.4 ± 3.3) que dans le groupe contrôle (7.3 ± 3.4 et 7.0 ± 3.7). De même le LMS et les MMS étaient significativement plus grands dans le groupe de blessure du LCA (4.7 ± 4.7 et 6.0 ± 3.4) que le groupe contrôle (0.9 ± 4.8 et 3.7 ± 3.6).

Dans les deux groupes, la pente tibiale osseuse externe était plus grande que la pente tibiale osseuse interne, mais la pente de tissu mou interne était plus grande que la pente de tissu mou externe.

Il a conclu que des pentes tibiales augmentées, tant osseux que les ménisques, sont des facteurs de risque pour la blessure du LCA. Comme le ménisque a tendance à corriger la pente observée vers l'horizontale, la perte du ménisque postérieur peut potentialiser cet effet en augmentant la pente fonctionnelle.

FIGURES

TABLES

ABBREVIATIONS

TERM	DESCRIPTION
MS	Meniscal slope
LTS	Lateral tibial slope
MTS	Medial tibial slope
LMS	Lateral meniscal slope
MMS	Medial meniscal slope
ACL	Anterior cruciate ligament
MRI	Magnetic resonance imaging
PTS	Posterior tibial slope
PTAA	Proximal tibial anatomical axis
TSAA	Tibial shaft anatomical axis
ICC	Intra class correlation coefficient
SD	Standard deviations
CNT	Control group

CONTENTS

3.1 INTRODUCTION

ACL injury occurs predominantly via non-contact mechanisms. Due to the high incidence of long-term sequelae of the ACL injury, including pain, instability, and the early development of osteoarthritis, identification of risk factors for ACL injury is an important step in the development of injury prevention [33].

Recently in the literature, there has been a great focus on anatomic risk factors. Posterior tibial slope (PTS) is commonly defined as the angle between a line fit to the posterior- inferior surface of the tibial plateau and a tibial anatomic reference line [14, 17, 18, 23, 30, 32].

Biomechanically, a higher tibial slope in the presence of a compressive load will generate a higher anterior shear component of the tibio-femoral reaction force, resulting in increased anterior motion of the tibia relative to the femur.

Because the ACL is the primary restraint against this type of motion in the knee, it logically follows that an increase in the posterior tibial slope will generate an increased load in the ACL. This hypothesis was first noted by Butler in 1980 [4].

Reliable clinical measurements of the posterior tibial slope are important for understanding ACL injury mechanisms. It is widely mentioned in the literature that ACL injured individuals have a greater posterior tibial slope than healthy controls [20].

It remains unclear whether the risk of non-contact ACL injury is increased in those with the increased slope in one or both compartments, and individual analysis of the compartments separately could be essential to understanding the functional consequences of tibial slope [21].

The medial and lateral PTS are not necessarily identical in one given knee and differences of as much as 27° have been reported in cadaveric studies [16].

Various models for PTS measurement on the conventional lateral radiographs have been described; however, it is still imprecise. Due to superimposition of the hemi-plateaus, the lateral tibial plateau is difficult to identify, and the separate assessment of the plateaus is not reliably possible on lateral radiographs [16].

The previous studies have validated different modalities for measuring posterior tibial slope [20]. No significant difference exists between radiographs, computed tomography, and magnetic resonance imaging (MRI); recent work has focused on MRI [20, 29]. Although lateral radiographs are better to assess the medial PTS, they are inadequate for reliable and separate

PTS and meniscal slope (MS) assessment [16]. Therefore, it is recommended to use the conventional MRI scans of the knee, as they allow simple assessment of each plateau separately, and provide the possibility to assess the MS reliably [15], while methods using three-dimensional computed reconstructions are time-consuming and complex [12].

The soft tissues (e.g., cartilage and meniscus) play a role in antero-posterior stability of the knee joint and may influence the functional tibial slope. The posterior horn of the menisci is thicker than the anterior horn, and this could decrease the postero-inferior slope [19].

This study aims to evaluate the correlation between the tibial slope and non-contact ACL injury using MRI, as well as to determine the effects of the menisci on the tibial slope.

It was hypothesized that the meniscus would reduce the differences in slope between the medial and lateral compartments of the same knee. In addition, it was hypothesized that the presence of the meniscus would correct the inclination of the bony tibial slope towards the horizontal.

3.2. MATERIALS AND METHODS

All patients referred to the Croix-Rousse Hospital between 2012 and 2015 for consideration of knee interventions were eligible for inclusion in the study. The inclusion criteria were an MRI scan, with adequate quality images available on the picture archiving and communication (PACS) system and a report detailing the status of the ACL. Exclusion criteria were osteoarthritis, patients with open physes or under the age of 18 years, MRI evidence of intra-articular pathology besides ACL tear, prior surgery to the involved knee, and those where the scanned length of the tibia was insufficient for calculation of the tibial axis.

Two groups of patients were thus established. The study group consisted of 100 patients (67 males and 33 females) with MRI confirmed isolated partial or complete rupture of the ACL. Patient age in this study group ranged from 18 to 63 (Mean ± SD, 33.7 ± 10.8). The control group consisted of 100 patients whose major complaint was patellofemoral pain (52 males and 48 females), and whose MRIs revealed an intact ACL. Patient age in this control group ranged from 18 to 86 (Mean ± SD, 43.6 ± 15.9).

MRIs were obtained from a single 1.5-T MRI scanner (manufacturer- supplied quadrature head coil, Siemens Aera Medical Systems). MRIs were obtained with the following parameters: for the coronal plane, slice thickness: 3.5 mm for 150 mm, TE: 13 ms, TR: 1800 ms. For the intermediate weighted sagittal plane, slice thickness: 1.5 mm for 170 mm, TE: 39 ms, TR: 1670 ms. Proton density sagittal slices were used to measure the angles.

All measurements of the bony tibial slope and meniscal slope angles were carried out using the annotation tools on the PACS provided by the hospital, which allows tracing of the anatomical landmarks, connecting regions of interest, and measurements of different angles. Three sagittal images were chosen from the corresponding axial cuts at the joint line for three different cut regions: the mid-sagittal cut, which use for calculating the proximal tibial anatomic axis (PTAA) (**Fig. 3.1**), the mid-lateral tibial plateau cut (LTP) (**Figs. 3.2, 3.3**), and the mid-medial tibial plateau cut (MTP) (**Figs. 3.4, 3.5**).

Two independent reviewers, blinded to subjects' details, calculated the angles on each MRI using a modified Hashemi method described previously by Lustig et al. [21]. The first observer performed two sets of measurements for each subject, 2 weeks apart. The second observer, blinded to the results of the first, repeated the measurements in a random specimen order.

To establish the tibial slope, we used PTAA which demonstrates the best correlation with the tibial shaft anatomic axis (TSAA) [6]. The PTAA is described on the mid-sagittal cut by a line joining the midpoint between the anterior and posterior tibial cortices at the level of the tibial tuberosity and at another level 5 cm more distal. The angle between the tibial axis and the horizontal was then calculated (PTTA-H Angle). This angle was used to transfer the PTAA among different images.

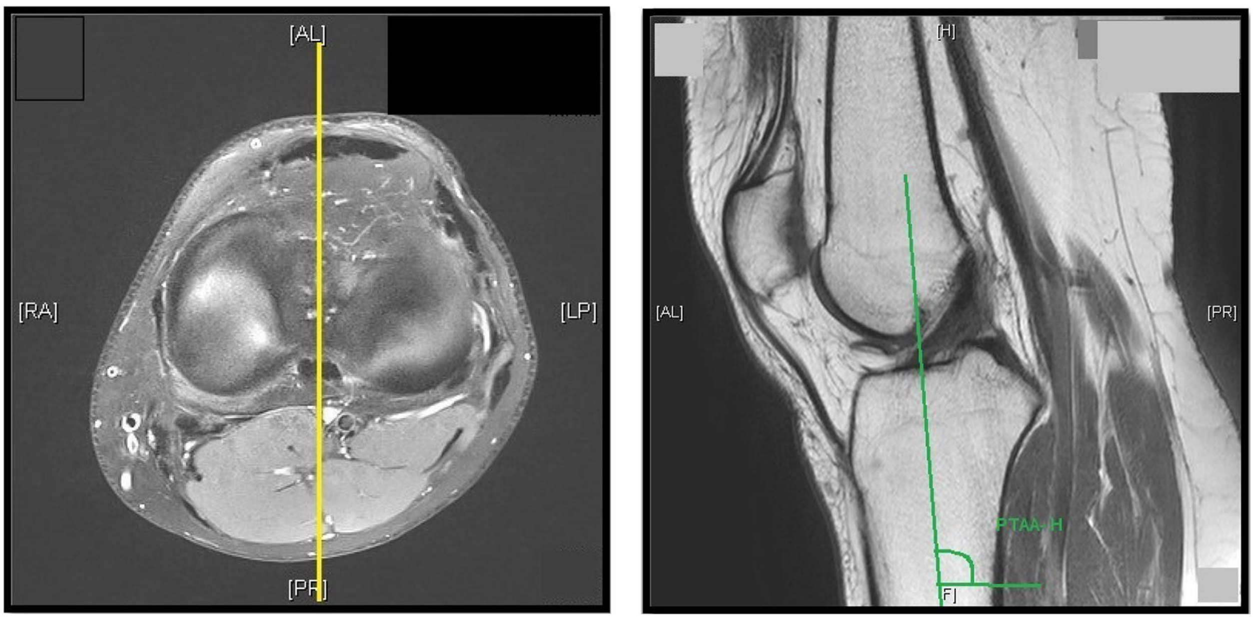

Fig. 3.1: Mid-sagittal image was chosen from the axial cut at the joint line. The PTTA was defined as a line through the midpoints between the two tibial cortices at the level of tibial tuberosity and at 5 cm more distal. The angle between the PTAA and the horizontal was also calculated (PTTA-H).

The MTP and LTP cuts were used to measure the medial and lateral tibial slopes (MTS, LTS), respectively. The PTAA was superimposed onto these cuts by means of the PTTA-H angle. The tibial slope in each compartment was measured as the angle between a line connecting the highest points of the anterior and the posterior parts of the tibial plateau, and a line perpendicular to the PTTA. A posterior inclination to the line perpendicular to the PTAA was assigned a positive value, while an anterior inclination was assigned a negative value.

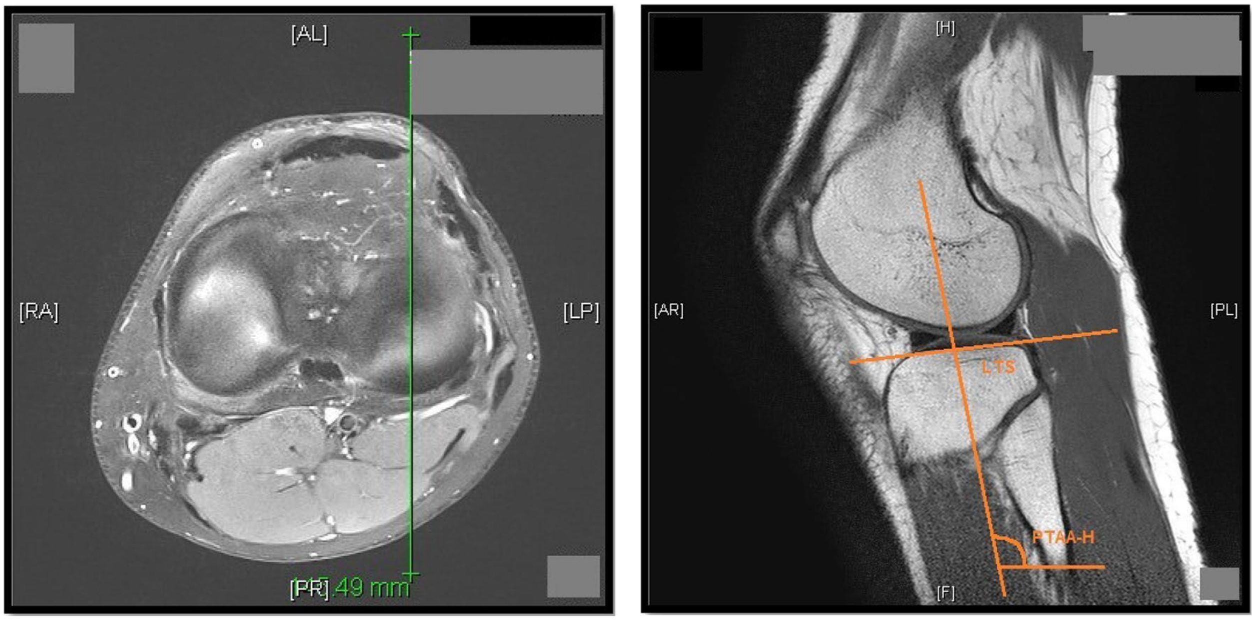

Fig. 3.2: Sagittal image was chosen from the axial cut at the joint line in the mid-lateral plateau and the PTAA was superimposed on the selected image by means of the PTAA-H angle. The LTS was calculated as the angle between a line joining the high points of the anterior and posterior lateral tibial plateau and a line perpendicular to the PTTA.

All measurements were positioned as an overlay and remained in a fixed position on the complete image series. The lateral meniscal slope (LMS) and medial meniscal slope (MMS) were defined in the same manner as the PTS. A line joining the superior edge of the meniscosynovial border of the anterior and posterior horns of the meniscus in the sagittal plane was chosen instead of the tibial plateau cortex.

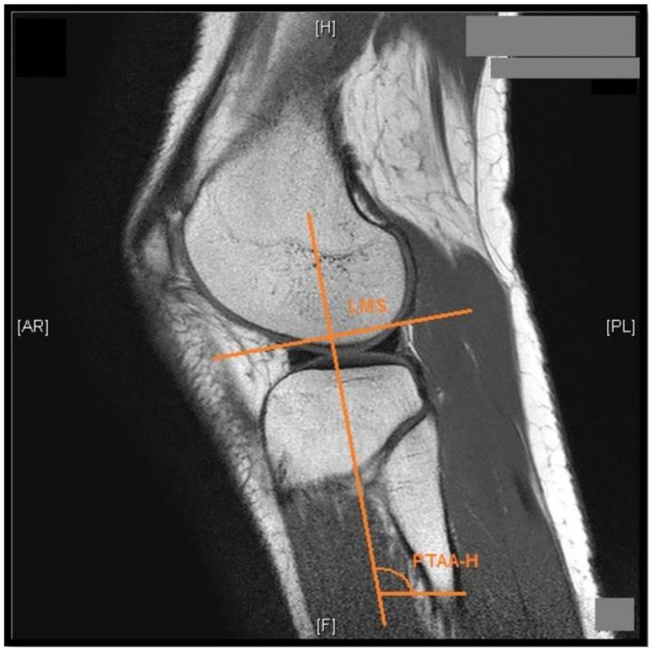

Fig. 3.3: After superimposition of the PTTA by means of the PTAA-H, the LMS was calculated as the angle between a line joining the highest points of the anterior and posterior horns of the lateral meniscus and a line perpendicular to the PTAA.

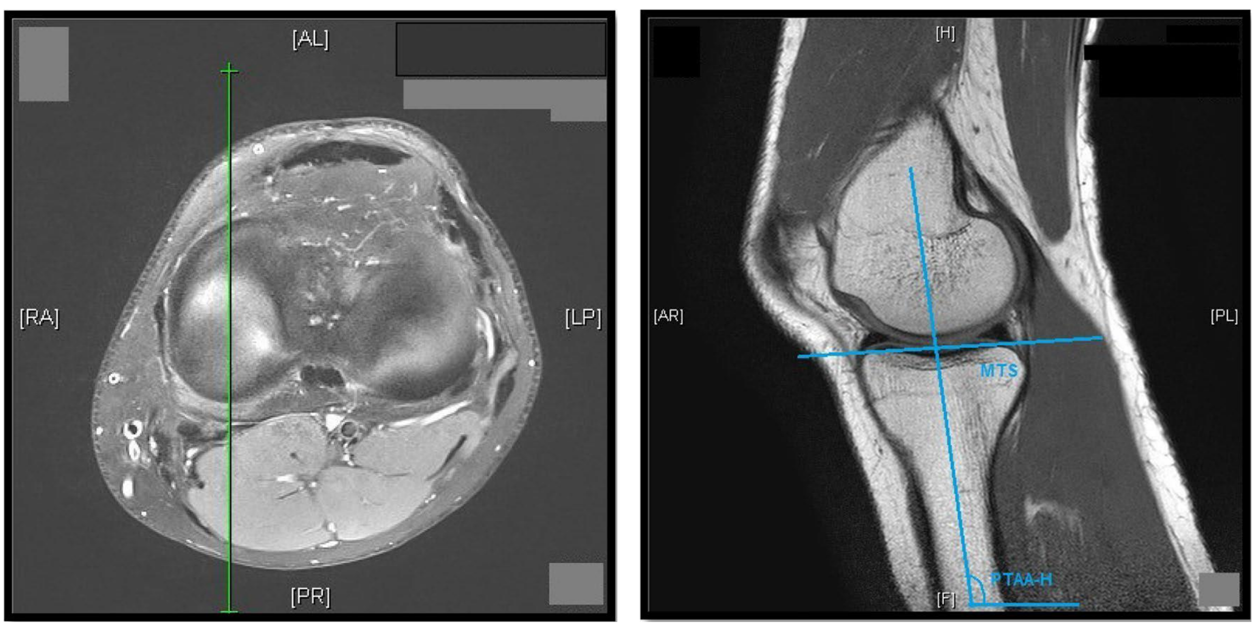

Fig. 3.4: Sagittal image was chosen from the axial cut at the joint line in the mid-medial plateau and the PTAA was superimposed on the selected image by means of the PTAA-H angle. The MTS was calculated as the angle between the tangent line to the high points of the anterior and posterior region of the medial tibial plateau and a perpendicular line to the PTAA.

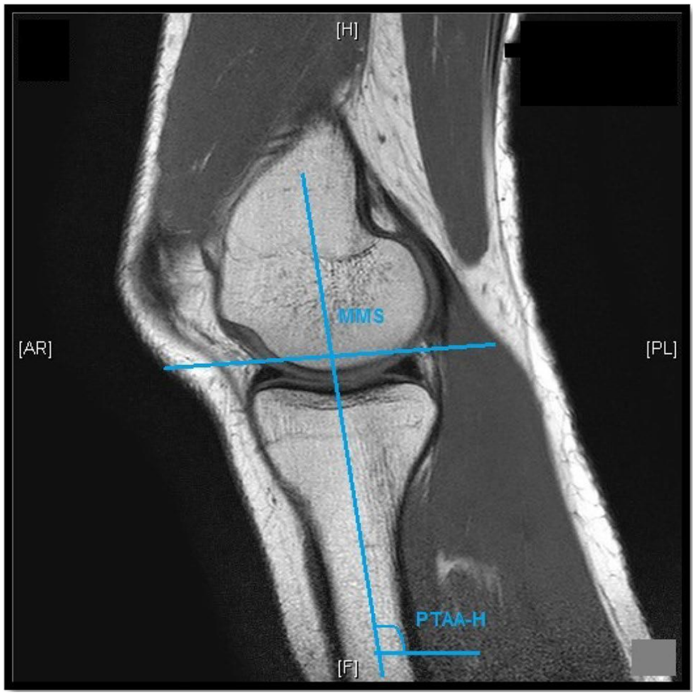

Fig. 3.5: After superimposition of the PTTA by means of the PTAAH, the MMS was calculated as the angle between the tangent line to the highest points of the anterior and posterior horns of the medial meniscus and perpendicular line to the PTAA.

3.2.1. STATISTICAL ANALYSIS

The PTS and MS angles were reported as mean angles with standard deviations. Data were statistically analyzed using SPSS for Windows statistical package (version 11.5; SPSS, Chicago, IL, USA). The assumption of normality was assessed with the Kolmogorov–Smirnov tests. Intra-observer and inter-observer reliability were tested by means of Intra-class Correlation Coefficient (ICC) to establish whether the mean slope was altered between repeated measurements of the two observers.

Independent two-sample student t-test was used to compare the four variants between the two groups. We calculated a sample size of 95 subjects was required, to achieve 90% power to reject the null hypothesis ($\alpha = 0.0001$).

3.3. RESULTS

The test of normality revealed that all measured parameters for both groups were normally distributed ($p < 0.0001$). The data were initially analyzed for each reviewer and then the parameters were compared between the two groups.

3.3.1. INTRA-OBSERVER AND INTER-OBSERVER RELIABILITY

The inter-observer ICC for all variants of the ACL group ranged from 0.89 to 0.91 and for the control group from 0.87 to 0.90. Similarly, the intra-observer ICC was high (0.88–0.93) which reveal a strong agreement between observers for all measurements.
The means, standard deviations (SD), and ranges for the repeated measurements LTS, MTS, LMS, and MMS for the examined and control groups are shown in **Table 3.1**.

For the ACL injury group, the LTS ranged from 1.9° to 15.8° and the MTS ranged from 1.4° to 16°, while the LMS ranged from −5.6° to 13.8° and the MMS ranged from −2.2° to 14.5°. Similarly, for the control group, the LTS ranged from 0° to 15.4°, and the MTS ranged from −0.6° to 15.0°, while the LMS ranged from −12.5° to 12.6° and the MMS ranged from −4.2° to 11.5°. In the analysis of the ACL injury group, the LTS was larger than the MTS, but the LMS was smaller than MMS. In the control group, the LTS was also larger than the MTS and the LMS was smaller than MMS (**Fig. 3.6**).

Table 3.1: Measurements of the bony and soft tissue slopes in both groups (in degrees).

GROUP	VALUE	LTS	MTS	LMS	MMS
ACL	MEAN ±SD	10.4 ± 3.1	9.4 ± 3.3	4.7 ± 4.7	6.0 ± 3.4
	RANGE	1.9 - 15.8	1.4 - 16	-5.6 - 13.8	-2.2 - 14.5
CONTROL	MEAN ±SD	7.3 ± 3.4	7.0 ± 3.7	0.9 ± 4.8	3.7 ± 3.6
	RANGE	0 - 15.4	-0.6 – 15.0	-12.5 -12.6	-4.2 – 11.5

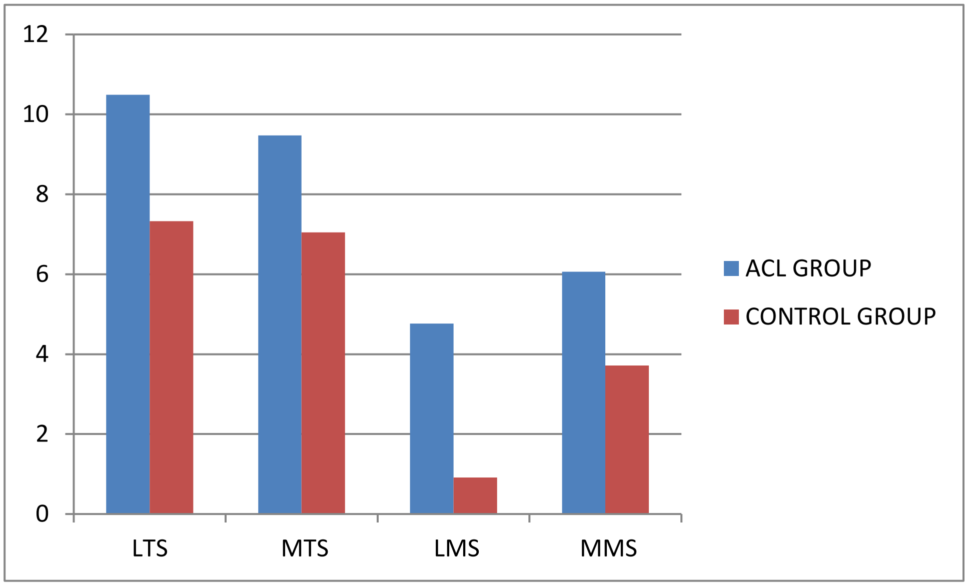

Fig. 3.6: Comparison of the means of the different slope angles between the ACL group and the control group (Refer to the text for details).

3.3.2. COMPARISON OF THE VARIANTS OF THE TWO GROUPS

By direct comparison of the two groups, using independent a two-sample Student's t-test, the LTS and MTS were significantly greater in the ACL injury group than the control group ($p < 0.0001$). Similarly, the LMS and MMS were significantly greater in the ACL injury group than the controls ($p < 0.0001$).

3.4. DISCUSSION

The most important finding of this study is that the lateral and medial bony and soft tissue slopes were all significantly higher in the ACL injured group compared to the control group. In both groups, the lateral bony tibial slope was greater than the medial bony tibial slope, but the medial soft tissue slope was greater than the lateral soft tissue slope. These findings are generally consistent with the published literature (**Table 3.2**).

Regarding the bony slope, Brandon et al. compared the radiographic posterior-inferior tibial slope, as measured on plain radiographs, between ACL injured subjects and controls [2]. They found an increased slope in the ACL injured group, and that within the ACL injured group, increased slope correlated with increased severity of the pivot shift. Stijak et al. using radiographs to establish the PTAA and then MRI to measure the bony slope in each compartment found an increased lateral bony slope in ACL injured subjects [24]. Hashemi et al. in an MRI study, found increased lateral tibial plateau slope and decreased medial plateau concavity in the ACL injured group in both sexes, as well as an increased medial slope in ACL injured males [13].

Similar results have also been reported in the pediatric population [6, 22]. Not all studies have supported these findings. Blanke et al. in a study of recreational skiers, found no difference in the lateral or medial slope, or medial plateau concavity, between ACL injured and non-injured subjects [1]. Hudek et al. examined not only the bony tibial slopes, but also the influence of the menisci or the soft tissue slope [15]. In contrast to the aforementioned studies, they found no difference between ACL injured and healthy controls with regard to the bony lateral and medial slopes. However, they found increased lateral meniscal slope in the ACL injured group. Lustig et al. examined the effect of the meniscus on the observed slope in non-ACL injured subjects [21]. In line with the findings of our study; they found the meniscal slope to be more horizontal than the bony slope in both compartments, with the lateral meniscal slope closer to horizontal than the medial meniscal slope. Bonnin and Dejour investigated the impact of the tibial slope on knee biomechanics, they found a 6 mm increase in anterior translation for each 10° increase in slope in healthy and ACL deficient knees [8]. In a cadaveric study, Giffin noted an increase in anterior tibial resting position with the increased tibial slope that was accentuated under an axial load [10].

Table 3.2: Review of the different MRI studies comparing tibial and meniscal slopes of ACL injured subjects: Exam: examined group, Cnt: control group

STUDY	YEAR	No. OF SUBJECTS	LTS	MTS	MMS	LMS	COMMENT
Stijak et al [24]	2008	33 injury vs. 33 control	Exam: 7.5 ± 3.3˚ Cnt: 4.3 ± 2.2˚	Exam: 5.2 ± 3.6˚ Cnt: 6.5 ± 3.2˚	- -	- -	ACL group had greater LTS while intact ACL group had greater MTS
Khan et al [17]	2011	73 injury vs. 51 control	Exam: 4.6 ± 3.0˚ Cnt: 2.6± 2.4˚	Exam: 5.0 ± 2.4˚ Cnt: 4.8± 3.5˚	- -	- -	LTS steeper in the injured compared to controls
Hudek et al [15]	2011	55 injury vs. 55 control	Exam: 5.6˚ Cnt: 4.9˚	Exam: 4.7˚ Cnt: 4.7˚	Exam: 1.3˚ Cnt: 0.1˚	Exam: 1.8˚ Cnt: -1.7˚	Both PTS & MS were greater in ACL injured group than controls
Hohmann et al [14]	2011	272 injury vs. 272 control	Exam: 5.8 ± 3.5˚ Cnt: 5.6 ± 3.2˚		-	-	ACL group have greater PTS than control
Hashemi et al [13]	2010	49 injury Vs. 55 control	Exam Male 7.2± 2.7˚ Female 8.4± 2.8˚ Cnt: ˚ Male 5.4± 2.7˚ Female 7.0± 3.0˚	Exam Male 5.9± 2.7˚ Female 6.8± 3.6˚ Cnt: Male 3.6± 3.1˚ Female 5.9± 2.9˚	- -	- -	ACL injured group had greater LTS & MTS than controls
Lustig et al [21]	2013	101 anterior knee pain	5.5 ± 4.7˚	5.1 ± 4.1˚	1.8± 4.3˚	-0.1± 5.7˚	LTS larger than MTS Soft tissue slope more horizontal in the lateral compartment
Our study	2016	100 injury Vs 100 control	Exam: 10.4 ± 3.1˚ Cnt: 7.3± 3.4˚	Exam: 9.4 ± 3.3˚ Cnt: 7.0± 3.7˚	Exam: 6.0 ± 3.4˚ Cnt: 3.7± 3.6˚	Exam: 4.7 ± 4.7˚ Cnt: 0.9± 4.8˚	Both bony & soft tissue slopes were greater in ACL injured group than controls

The effects of patient demographics, such as gender and age on the tibial slope, have not been fully elucidated. Females are at greater risk of non-contact ACL injury and a steeper tibial slope has been observed in females [21]. Multiple studies have shown that women have a greater propensity for ACL injury compared to their male counterparts [11, 13, 15, 24, 33]. It has been suggested that a possible risk factor for this observation is that women have a narrower notch than men and even smaller ACLs. Differences in slope between the medial and lateral compartments may also have biomechanical consequences. Under a compressive load, the lateral femoral condyle has been postulated to slide posteriorly due to increased LTS, pivoting around the medial femoral condyle. The resultant external femoral rotation has been shown to place excess strain on the ACL [9, 23].

An increased posterior slope is a risk factor not only for an ACL tear, but also for failure of ACL reconstruction. Webb et al. found an increased risk of failure or contralateral injury associated with increased tibial slope, which was most apparent with the posterior slope in excess of 12° [31]. Similarly, Christensen et al. found the increased lateral slope to be associated with a risk of early failure, regardless of graft type [5]. Slope leveling osteotomy has been proposed to correct this risk factor in repeat revision surgery [9, 28].

The importance of the meniscal contribution to slope and knee biomechanics remains unclear. While Lustig demonstrated more horizontal meniscal slopes when compared to the bony slopes, this MRI-based study could not evaluate the effect of joint loading and meniscal mobility [21]. Song has defined the abnormal lateral plateau slope as a risk factor for a high-grade pivot shift [27]. Loss of the posterior lateral meniscal root also increases lateral compartment anterior translation during a pivot shift maneuver [25]. Under load, loss of the meniscal root could convert the effective functional slope from the meniscal slope to the bony slope, which may explain these findings. Song, in a separate study, also found an increased medial meniscal slope to be a risk factor for ramp lesions, particularly when time to surgery was greater than 6 months [26].

An understanding of the anatomical risk factors for ACL injury and treatment failure is important. While some factors, such as the width of the intercondylar notch, are not readily modifiable, their identification may help to target proven prevention strategies towards high-risk individuals, in the same manner in which they are targeted towards high-risk sports. As a risk factor, the increased tibial slope is potentially modifiable by osteotomy. Such intervention should be considered in cases of excessive slope, particularly after the loss of the menisci; however, the appropriate threshold for intervention remains unclear.

One of the greatest strengths of using MRI for this application is the ability to visualize the surface geometry of the articular cartilage, which represents the functional point of the tibio-femoral articulation. Our study presents a reliable method for measurement of the tibial and meniscal slopes in both knee compartments, which could be developed as a predictive tool for ACL risk. The aims of future research relating PTS to ACL injury risk should be to establish not only the extent of the role of tibial slope in injury, but also to which that risk can be minimized by preventive measures, such as neuromuscular training [33].

This study is subject to a number of limitations. First, all MRI scans were performed in a recumbent position. Weight-bearing may affect the meniscal height both anteriorly and posteriorly and thus alter the measured meniscal slope. Furthermore, the control group consisted of patients with patello-femoral pain, but no intra articular pathology as seen on MRI scans. While a similar group has been used in multiple previous studies [2, 15, 21, 24], these patients may, in fact, have tibial slope characteristics that differ from a true asymptomatic population.

3.5. CONCLUSION

This study confirmed that the tibial bony and soft tissue slopes can be measured reliably using an MRI-based method. Increased tibial slopes, both bony and meniscal, are risk factors for ACL injury. As the meniscus tends to correct the observed slope towards the horizontal, loss of the posterior meniscus may potentiate this effect by increasing the functional slope.

3.5.1. Compliance with ethical standards

Conflict of interest The authors declare that they have no competing

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Chapter 4

CT COHORT STUDY

INCIDENCE AND PATTERNS OF MENISCAL TEARS ACCOMPANYING THE ANTERIOR CRUCIATE LIGAMENT INJURY: POSSIBLE LOCAL AND GENERALIZED RISK FACTORS

CT Cohort Study

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ABSTRACT

Purpose: Injury to the anterior cruciate ligament (ACL) is frequently accompanied by tears of the menisci. Some of these tears occur at the time of injury, but others develop over time in the ACL-deficient knee. The aim of this study was to evaluate the effects of the patient characteristics, time from injury (TFI), and posterior tibial slope (PTS) on meniscal tear patterns.

Our hypothesis was that meniscal tears would occur more frequently in ACL-deficient knees with increasing age, weight, TFI, PTS, and in male patients.

Methods: Of the ACL-injured patients, 362 were analyzed, and details of meniscal lesions were collected. The medial and lateral tibial slopes (MTS, LTS) were measured via computed tomography. Patient demographics, TFI, MTS, and LTS were correlated with the diagnosed meniscal tears.

Results: Of the patients, 113 had a medial meniscus (MM) tear, 54 patients had a lateral meniscus (LM) tear, 34 patients had tears of both menisci, and 161 patients had no meniscal tear. The most common tear location was the posterior horn (PH) of the MM, followed by tear involving the whole MM. Patient age, BMI, and TFI were significantly associated with the incidence of MM tear. Female patients had a higher incidence of injury than males in all tear sites except in the body and PH. Male patients had more vertical and peripheral tears. The median MTS and LTS for patients with MM tears were 7.0°and 8.7°, respectively, while those of patients with LM tears were 6.9° and 8.1°. Steeper LTS was significantly associated with tears of LM and of both menisci.

Conclusion: Older age, male sex, increased BMI, and prolonged TFI were significant factors for the development of MM tears.
An increase in the tibial slope, especially of the lateral plateau, seems to increase the risk of tear of the LM and of both menisci.

Level of evidence: Level III.

Keywords: Knee. ACL injury. Meniscus tear. Tibial slope. Time from injury

RÉSUMÉ

La blessure au ligament croisé antérieur (LCA) est fréquemment accompagnée par les lésions du ménisque. Certaines de ces larmes sont arrivées au moment de la blessure, mais d'autres se développent au fil du temps dans le genou de LCA-blessé.

Le but de cette étude était d'évaluer les effets des caractéristiques patientes, le temps de la blessure (TFI) et la pente tibiale postérieure (PTS) sur des modèles de larme de ménisque.

Notre hypothèse était que les larmes de meniscal arriveraient plus fréquemment dans des genoux de LCA-blessé avec l'âge croissant, le poids, TFI, PTS et dans des patients masculins.

Des patients du LCA-blessé, 362 ont été analysé et les détails de lésions ménisques ont été rassemblés. Les pentes tibiales interne et externe (MTS, LTS)) ont été mesurées via la tomographie. Des données démographiques patientes, TFI, MTS et LTS étaient corrélés avec les larmes de ménisque diagnostiquées.

Des patients, 113 avaient des lésions de ménisque interne(MM), 54 patients avaient des lésions de ménisque externe (LM), 34 patients avaient les larmes tant de deux ménisques, que de 161 patients n'avaient aucune larme de ménisque.

L'emplacement de larme le plus commun était la corne postérieur (PH) de MM, suivi par la larme impliquant le MM entier. L'âge patient, BMI et TFI a été significativement associé à l'incidence de larme de MM.

Les patients féminins avaient une incidence plus haute de blessure que des mâles dans tous les sites de larme sauf dans le corps et le PH. Les patients masculins avaient des larmes plus verticales et périphériques. Les médianes MTS et de LTS pour des patients avec des larmes de MM était 7.0°and 8.7 °, respectivement, tandis que ceux de patients avec des larmes de LM étaient 6.9 ° et 8.1 °. La LTS plus raide a été significativement associée aux larmes de LM et des deux ménisques.

Il est concluent que le plus âge, le genre masculine, BMI augmenté et TFI prolongé étaient des facteurs significatifs pour le développement des larmes de MM.

Une augmentation de la pente tibiale, particulièrement du plateau latéral, semble augmenter le risque de la larme de LM et des deux ménisques.

FIGURES

TABLES

ABBREVIATIONS

TERM	DESCRIPTION
ACL	Anterior cruciate ligament
AH	Anterior horn
ATT	Anterior tibial translation
BMI	Body mass index
CT	Computed tomography
ICC	Intraclass correlation coefficient
ISAKOS	International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine
LM	Lateral meniscus
LTS	Lateral tibial slope
MM	Medial meniscus
MTS	Medial tibial slope
ns	Non-significant
PACS	Picture archiving and communication system
PH	Posterior horn
PTAA	Proximal tibial anatomic axis
PTS	Posterior tibial slope
SD	Standard deviations
TFI	Time from injury

CONTENTS

4.1. INTRODUCTION

The anterior cruciate ligament (ACL) is the primary restraint to anterior tibial translation (ATT), providing 85% of the total restraining force to anterior drawer [1]. Isolated ACL tears are uncommon, with approximately 50% accompanied by meniscal tears due to the close anatomic and functional relationships of these structures [2].

The menisci are important structures within the knee, with complex biomechanical functions. They are thought to carry 40–70% of the load across the knee, and they have a role in shock absorption, proprioception, and enhancement of stability [3].

Preservation of meniscal tissue and function is paramount for long-term joint function, especially in active patients. Early repair of tears of the posterior horn (PH) of the lateral meniscus (LM) significantly improve loading profiles in the lateral compartment, and may help to prevent the cartilage degeneration and osteoarthritis associated with partial meniscectomy [2].

Understanding the demographic and morphometric differences in ACL-deficient patients with meniscal lesions becomes more important in injury prevention and treatment. Many studies have analyzed predictors of these injuries and demonstrated an association between meniscus tears and male sex, obesity, increased age, varus malalignment, and increased time from injury (TFI) [2, 4–8].

A limitation of these studies is that meniscus tears were considered a binary finding (i.e., tear vs. no tear). However, different patterns of meniscal tears in ACL-injured subjects may be associated with different demographic and historical risk factors. Identification of such risk factors may help physicians recognize patients at risk of more significant or irreparable meniscal tears.

Furthermore, patients may present with knee pain and isolated meniscal tears, without any history of trauma, implying other causative factors. One may hypothesize that the bony morphology of the knee, including the posterior tibial slope (PTS), may contribute to the development of meniscal tears.

The purpose of this study to document the incidence and distribution of meniscal lesions accompanying ACL tears in a large patient cohort, and to test for associations between these lesions and patient age, gender, body mass index (BMI), time from injury (TFI), and medial and lateral tibial slope (MTS and LTS).

Our hypothesis was that meniscal tears would occur more frequently in ACL-deficient knees with increasing age, weight, TFI, PTS, and in male patients. We further hypothesized that increased PTS and TFI would be associated with more significant meniscal lesions.

4.2. MATERIALS AND METHODS

4.2.1. STUDY DESIGN

A retrospective cohort study was performed to analyze the association between different patterns of meniscal tears in ACL-injured subjects, and potential demographic and historical risk factors. As all data were collected retrospectively from medical records, Institutional Review Board approval was not required at our institution.

4.2.2. PATIENT'S SELECTION

All patients undergoing ACL reconstruction in our institution between 2012 and 2015 were recruited to this study.

The pre-operative clinical notes were reviewed to collect patient age, gender, BMI, and TFI data.

The pre-operative clinical and radiological examination findings, as well as the intra-operative findings, were also reviewed. All data were recorded on evaluation forms.

Patients with either partial or complete ACL rupture in the affected knee, as established by arthroscopy, were included in the study. Exclusion criteria were patients less than 18 years old, a history of previous surgery involving partial meniscectomy, other ligamentous lesions, or signs of osteoarthritis.

Seven patients were also excluded due to an incomplete or ambiguous documentation of meniscal status.

A total of 362 consecutive patients with partial or complete rupture of ACL injury were included, and were divided into four groups according to the involved meniscus: group 1 with medial meniscal (MM) tear, group 2 with lateral meniscal (LM) tear, group 3 with tears of both menisci, and group 4 with no meniscal tear.

4.2.3. MENISCAL TEAR CLASSIFICATION

In all patients, meniscal lesions were confirmed arthroscopically using a standard probe and documented according to the ISAKOS classification [9]. Tears were documented occurring in the medial or lateral meniscus. In addition, each meniscus was subdivided into three parts: the anterior horn, the body, and the posterior horn.

We further categorized the type of meniscal tear as vertical, horizontal, peripheral (meniscocapsular and ramp lesions), oblique, flap, radial, or complex. Other variations such as bucket handle and degenerative tears were also recorded.

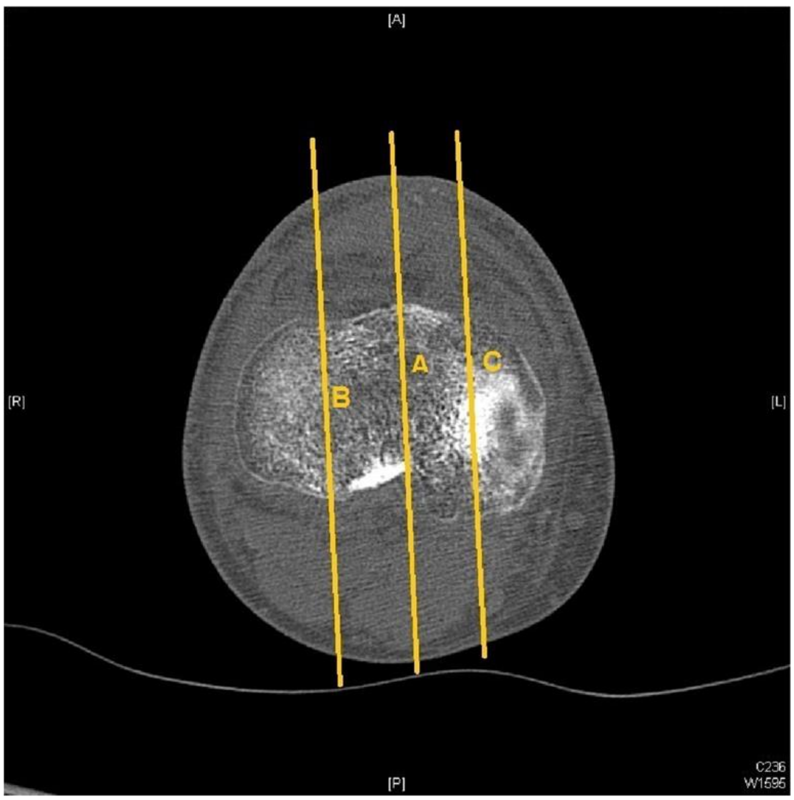


Fig. 4.1: Three CT axial cuts of the tibia at the superior joint line were taken to select the corresponding midsagittal (A), the mid-medial sagittal (B), and the mid-lateral sagittal images (C).

4.2.4. TIBIAL SLOPE MEASUREMENT

The recruited knees were scanned by a 256-computed tomography CT (Tube voltage 120 kV, current 250 mAs, slice thickness 0.6 mm, collimation 0.6 mm, response time 0.5 s, Philips

Brilliance ICT 256 slice). These archived CT images were analyzed and morphometric measurements were performed using a picture archiving and communication system (PACS; Centricity, GE Healthcare, Waukesha, Wisconsin) workstation with standard features, including the ability to adjust windows, change the zoom, and apply electronic calipers.
The MTS and the LTS were measured by two blinded radiologists using the modified mid-point method previously published by Lustig et al. [10]. Three sagittal slices were selected corresponding to the mid-sagittal (A), the mid-medial compartment sagittal (B), and the mid-lateral compartment sagittal cut (C) (**Fig. 4.1**). All sagittal slices were selected manually, and digital measurements were performed twice for each patient two weeks apart to assess the intra-observer reliability.

The proximal tibial anatomical axis (PTAA) was selected to establish the PTS. This axis has been shown to have the best correlation with the tibial shaft anatomic axis and reflect most accurately the mechanical axis of the tibia [11].

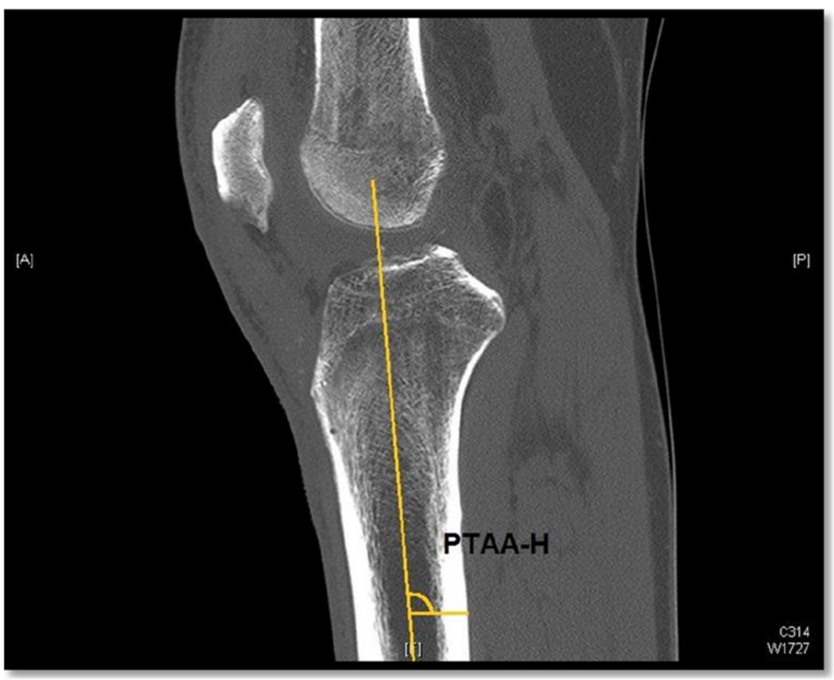


Fig. 4.2: The PTTA was defined as a line through the mid-points between the two tibial cortices at the level of tibial tuberosity and at 5 cm more distal. The angle between the PTAA and the horizontal was also calculated (PTTA-H).

The PTAA was established on the mid-sagittal cut by a line joining the mid-point between the anterior and posterior tibial cortices at the level of the tibial tuberosity and at another level 5 cm more distal. The angle subtended between the tibial axis to the horizontal was then calculated (PTTA-H angle) (**Fig. 4.2**). This angle was then used to transfer the calculated tibial axis to the medial and lateral sagittal cuts to assess the MTS and LTS, respectively. The tibial slope in each compartment was measured as the angle between a line perpendicular to PTAA and a line connecting the superior points of the anterior and posterior corresponding tibial plateau (**Fig. 4.3**). A posterior inclination was assigned a positive value, while an anterior inclination was assigned a negative value.

4.2.5. STATISTICAL ANALYSIS

Statistical analysis was performed using SPSS for Windows (version 11.5; SPSS, Chicago, IL, USA). Microsoft Excel was used to calculate statistical values and to create diagrams. Continuous variables were calculated as the mean ± standard deviation, and categorical variables were reported as count and percentages. The assumption of normality was assessed with Kolmogorov-Smirnov tests. Inter- and intra-observer reliabilities were tested by means of intraclass correlation coefficient (ICC). The Wilcoxon rank sum test and the chi-squared test were used to test the difference between the continuous and categorical variables. Kruskal-Wallis ANOVA test and post hoc tests were used to test the effects of age, sex, BMI, TFI, MTS, and LTS on the incidence, sites, and types of meniscal tears. The results of correlations and risk analysis were calculated separately, where the probability of this result, assuming the null hypothesis, was less than 0.05.

Fig. 4.3: Superimposition of the PTTA on each corresponding sagittal image by means of PTAA-H. Calculation of the MTS and LTS as the angle between a line joining the high points of the anterior and posterior tibial plateau and a line perpendicular to the PTTA.

4.3. RESULTS

The distribution of age, BMI, LTS, MTS, and TFI were tested using a one-sample Kolmogorov-Smirnov test. All variables were normally distributed except TFI ($p < 0.001$). The means, standard deviations (SD), and ranges are shown in Table (**4.1**).

4.3.1. DISTRIBUTION OF MENISCAL LESIONS

From 362 patients (238 male and 124 female), there were 113 patients with an isolated MM tear (group 1), 54 patients with an isolated LM tear (group 2), 34 patients with tears of both menisci (group 3), and 161 patients with no meniscal tear (group 4) (**Fig. 4.4**). The most common tear location of the MM was the PH, followed by tears of the whole meniscus. Similarly, tears of the LM tended to be distributed more posteriorly and involve mainly the PH, followed by the tears involving both the PH and body. Tears of the anterior parts of the menisci were seen least frequently. The distribution of meniscal tears across the different anatomical regions is shown in **Fig. 4.5**.

Table 4.1: The means, standard deviations (**SD**) and ranges of all the variables for all patients. BMI: Body Mass Index, MTS: Medial Tibial Slope, LTS: Lateral Tibial Slope, TFI: Time From Injury.

PARAMETER	AGE(years)	BMI($kg/m^{2)}$	MTS(˚)	LTS(˚)	TFI(months)
MEAN	32.1	24.0	9.1	7.6	11.7
SD	11.0	3.4	3.5	3.6	24.6
RANGE	18.0 - 61.9	17.5 - 37.6	1 - 18.9	-1.1 - 17.9	0.37 - 256.4

4.3.2. TYPES OF MM TEARS (GROUPS 1 AND 3)

After evaluating all 147 MM tears, the most common tear type was a vertical tear (33%), followed by bucket-handle tears (18%). We noted an equal proportion of peripheral and complex tears (12% each), while the degenerative tears represented the least common type (1%) (**Fig. 4.6a**).

4.3.3. TYPES OF LM TEARS (GROUPS 2 AND 3)

In 88 LM tears, vertical tears were observed in 27. In comparison with MM tears, there were less of bucket-handle tears (5%) but more horizontal tear among the LM tears than the MM (18 vs. 6%). As in the MM, the degenerative tears represented the least tear type (2%). Oblique tears had the same distribution for both sides (6%) (**Fig. 4.6b**).

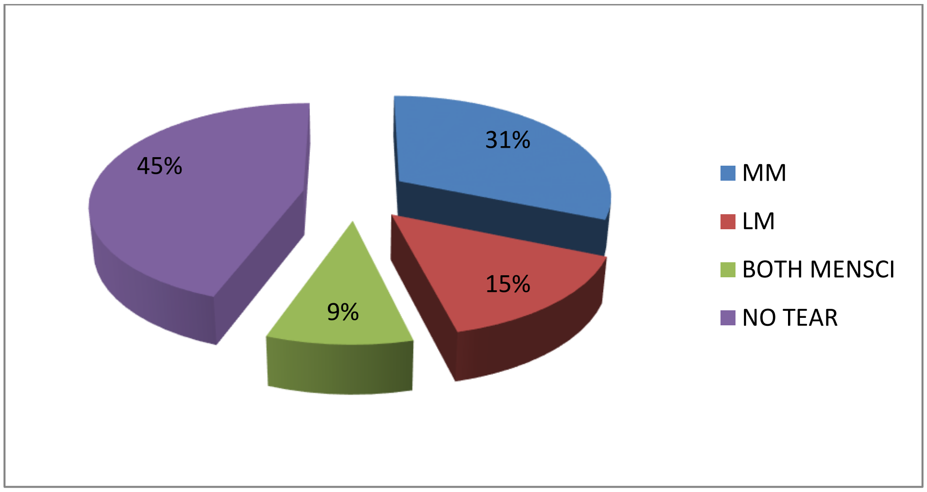
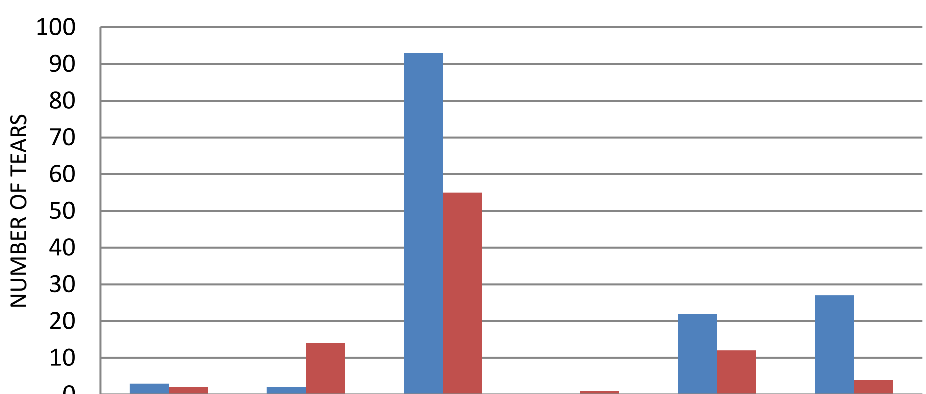
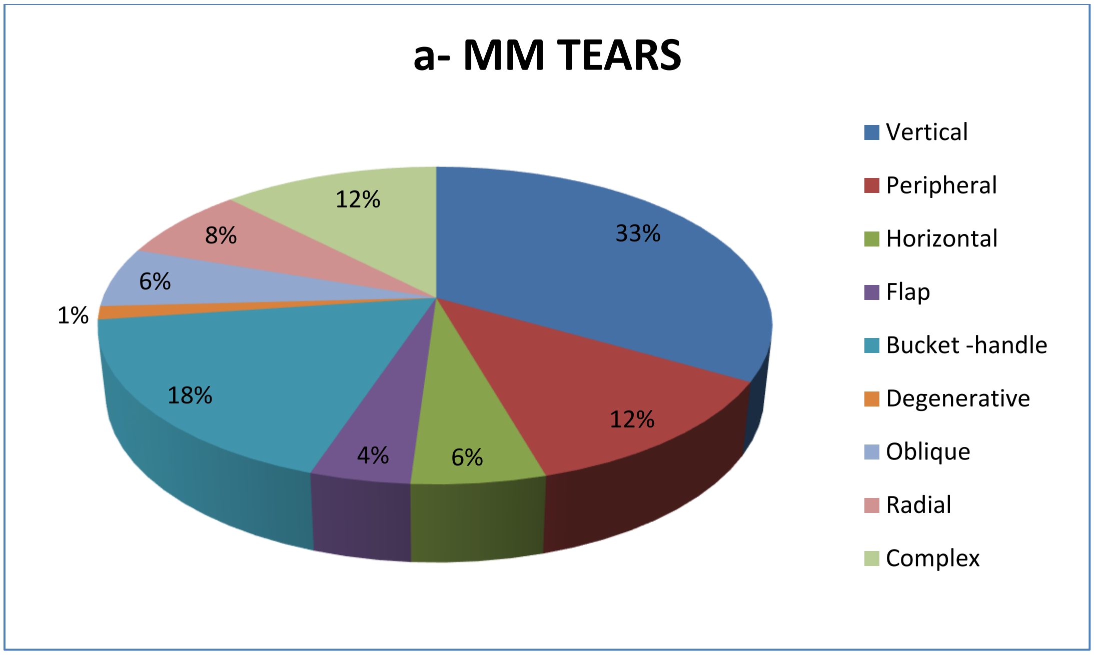


Fig. 4.4: Incidence of meniscal tears, MM: Medial meniscal tears, LM: Lateral meniscal tears.



	AH	BODY	PH	AH+BODY	PH+BODY	AH+BODY +PH
MM	3	2	93	0	22	27
LM	2	14	55	1	12	4

Fig. 4.5: Distribution of the meniscal tears. AH: Anterior horn, PH: Posterior horn.



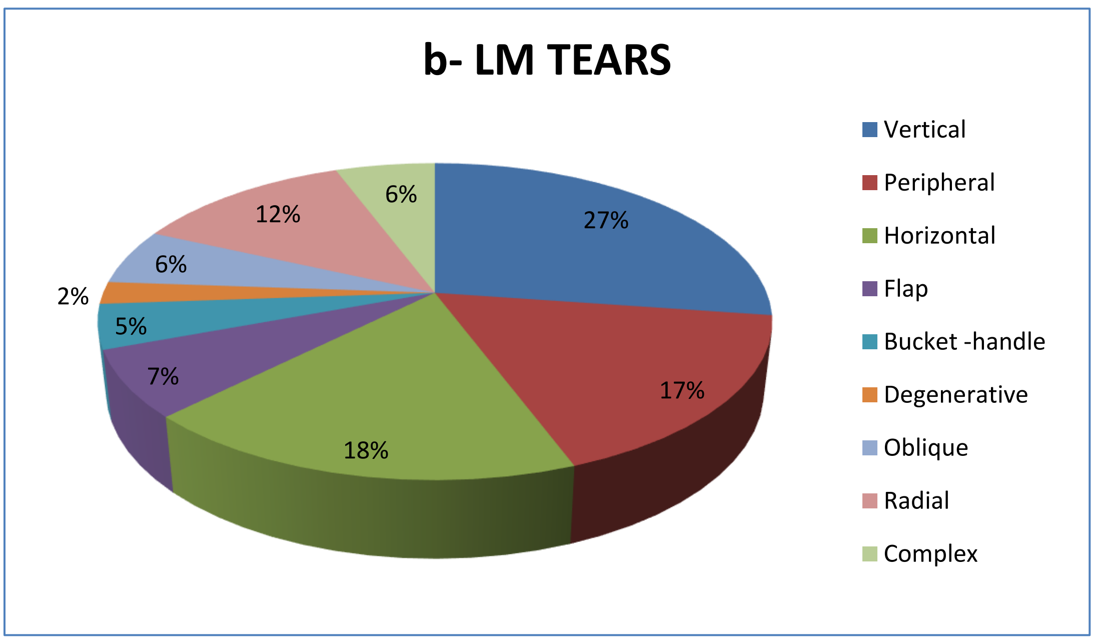


Fig. 4.6 a & b: Types of the meniscal tears. **a**: MM tears, **b**: LM tears.

4.3.4. PATIENT AGE

The median age of the patients with MM tears was 32.9 years while that of patients with LM tears was 29.7 (ns).

There was a significant relationship between patient age and the incidence of MM tears, with older patients having more MM tears (p = 0.002). However, there was no such relationship for the other groups.

4.3.5. GENDER

Using chi-squared test, there were significant associations between sex and the incidence of MM tears (p = 0.034), the incidence of the LM tears (p = 0.002), and the incidence of both meniscal tears (p = 0.005). Male patients predominated in all groups. The percentages of male and female patients having these tears were 44.5 and 33.1% (MM), 28.1 and 14.5% (LM), and 12.2 and 3.2% (both), respectively.

We also found a significant association between sex and tear sites (p = 0.002). Female patients had a higher incidence of injury to all tear sites except the body and posterior horn, and posterior horn tears. The percentages of male and female patients having tears in the different sites were 1.8 and 2.4% for anterior horn tears, 0.9 and 2.4% for body tears, 16.0 and 12.2% for posterior horn and body tears, 70.7 and 43.9% for posterior horn tears, and 10.4 and 39.0% for entire meniscus tears, respectively.

Finally, we found an association between sex and the type of the meniscal tear (p < 0.001). Male patients had more vertical, peripheral, and oblique tears, while females had a higher percentage of horizontal, flap, bucket-handle, degenerative, radial, and complex tears. The distributions of the tear types between male and female patients are shown in Table **(4.2)**.

4.3.6. BMI

The median BMI for the patients with MM tears was 24.2 while that of patients with LM tears was 23.8 (ns). BMI had a significant effect on the incidence of MM tears (p = 0.029), with patients with higher BMI having a higher incidence. Conversely, no effect of the BMI on the incidence of meniscus tears in the other groups. BMI did not affect the tear sites or types in any groups.

Table 4.2: The distribution of the tear types between male and female patients.

TEAR TYPE	MALE-FEMALE %
Vertical	42.4% - 7.3%
Peripheral	14.1% - 7.3
Horizontal	4.7% - 7.3%
Flap	3.8% - 4.9%
Bucket-handle	9.4% - 39.0%
Degenerative	0.9% - 2.4%
Oblique	6.6% - 4.9%
Radial	6.6% - 9.7%
Complex	11.3% - 14.6%

4.3.7. TIME FROM INJURY

The median TFI for patients with MM tears was 5.9 months while that for patients with LM tears was 4.7 months (ns).

TFI had a significant effect on the incidence of MM tears, with patients having a longer time to surgery more likely to have MM tears at the time of surgery (p = 0.031). Similar results were seen in group 2; however, this did not reach statistical significance (p = 0.056).

TFI did not influence tear site or type, with the exception of MM tear types. In this group, the Dunn and Sidák's post hoc test revealed that TFI was significantly higher for radial type (median = 18.73) than for peripheral (4.53) and oblique (3.55) types (p = 0.022).

4.3.8. TIBIAL SLOPE

Repeated measures analysis of variance showed strong agreement between the two raters for both the medial and lateral slopes (ICC 0.83 and 0.88 for MTS and LTS, respectively). Intra-observer reliability was also high for all measurements (0.89–0.93).

The median MTS and LTS for patients with MM tears were 7.0° and 8.7°, respectively, while those for patients with LM tears were 6.9° and 8.1°, respectively (ns).
The LTS has a significant effect on the incidence of LM tears. Patients with LM tears demonstrated greater LTS (median = 9.5°) compared to that of patients without tears (7.2°) (p = 0.003). Similarly, the LTS has a significant effect on the incidence of both meniscal tears (group

3), with patients in this group demonstrating greater LTS (9.3°) compared to that of the patients without tears (7.5°) (*p* = 0.007). The MTS did not influence the incidence of meniscus tears in any groups. Neither the MTS nor the LTS had an effect on the tear site or type in any group.

4.4. DISCUSSION

The overall incidence of meniscal tears in the present study was 55% (31% for MM, 15% for LM, and 9% for both menisci). This finding is consistent with rates in the literature [6, 7, 12]. Various mechanisms affect the frequency of medial and lateral meniscal tears, including lower limb alignment, load distribution, and delay of intervention. The incidence of LM tears remained relatively unchanged with time, while MM tears increased with time. Biomechanically, the MM is a secondary stabilizer of the knee against anterior displacement of the tibia in the ACL-injured knee and is subjected to anteroposterior shear forces. On the other hand, the more mobile LM is less likely to undergo these shear stresses [13]. This may account for the high incidence of MM tears, but further studies are necessary to prove this theory.

The most common tear location in the MM in our study was the PH, with the most common tear types being vertical tears (33%), followed by bucket-handle tears (18%), and peripheral tears (12%). These findings are in accordance with the current literature [14].

More bucket-handle tears were seen in the MM than in the LM. These findings are consistent with other studies, which found that MM tears were likely to be bucket-handle type regardless of the chronicity of the injury [12, 15]. Cerabona et al. have theorized that the recurrent trauma sustained by the MM while acting as a cushion in the ACL-deficient knee leads to PH tears [16]. This may be due to its relative immobility, resulting in a decreased ability to absorb shear stresses during subluxation of the tibial plateau during the pivot shift [3].

Regarding LM tears, the most common site for the tears was also the posterior horn. The most common tear types were vertical (27%) and horizontal tears (18%).

Radial tears were also more common in the LM (12 vs. 8%). It has been reported that approximately 15% of meniscal tears are radial tears, with 20% of these tears occurring in the PH of the LM, which may be more susceptible to radial tears due to a lack of ligamentous support [17]. Choi et al. reported that more radial tears were found in female patients than horizontal tears [18]. Radial tears of the meniscus significantly impair the load bearing function of the meniscus and cause the meniscus to be extruded under axial loads. If the meniscus is displaced, the incongruent bony articular surfaces come in direct contact, and subsequent damage to the articular cartilage will occur [19].

In our study, the LM showed more flap tears than the MM (7 vs. 4%). These results are supported by those of Ghodadra et al., who found that the full-thickness LM tears were more often flap-type tears [12].

Several factors are reported to increase the risk of meniscal tears in ACL-deficient patients. These include older age, male gender, increased body weight, time from injury, and repetitive activities [2, 5, 8, 20, 21].

We found increasing age to be associated with increased medial but not lateral meniscal tears regardless of the location of the tear. For the different lesion types, the age seemed homogenous. In contrast, Feucht et al. observed a higher risk for LM tears in younger patients [2], and other authors have found no correlation between age and meniscal injury [22].

There is a general belief of a strong effect of aging on the menisci in the literature. These effects may include vascular changes [23], biochemical changes [24], and degenerative changes [25]. The patients in our study, however, were relatively young, and degenerative tears were uncommon.

We also observed increased meniscal injury in male patients across all groups. Other authors, however, have found no such association [26]. Male patients had a higher incidence of injury in the body and posterior horn of both menisci and show more vertical and peripheral tears than females. This observed injury pattern may be explained by a lesser degree of ACL resilience in women, leading to ACL rupture at smaller forces with less associated meniscal injury [27]. On the other hand, the patterns could be due to less-resilient meniscal tissue and contraction difference in quadriceps or hamstring muscles in males [28]. Further investigation is needed to clarify the tissue-level influence on this potential gender difference.

In our study, increased BMI was also associated with an increased incidence of MM tears. Generally, obesity has an unfavorable effect on the knee joint, and previously, BMI and weight equally predicted meniscal injury [29]. Consequently, Ford et al. [5] reported a significant correlation between meniscal tear and increasing BMI.

Chen, however, found no correlation between BMI and meniscal or chondral injury, and suggested that higher BMI patients may be less active and thus less at risk for further injury [4]. There is a potential biomechanical explanation for the relationship between BMI and meniscal tears, in that, as the BMI increases, the torque in the knee joint during rotation may increase, and theoretically may cause more meniscal injury [18].

An increased interval between injury and surgery has also been shown to increase the frequency and severity of meniscal injuries [26].

Our study confirms that a delay in surgical treatment is associated with a higher incidence of MM tears. Our results are in accordance with the results of other studies that reported an increased incidence of MM tears in chronic (70–78%) compared to acute injuries (30–45%) [20, 30–32]. Similarly, our study supports previous reports that LM tears remain fairly constant with respect to TFI [26, 30, 33]. These findings support the notion that most LM tears occur at the time of the injury during the subluxation of the lateral compartment, while further MM tears occur due to the role of the MM as a secondary stabilizer in the ACL-deficient knee. Anatomically, the MM is attached firmly to the joint capsule and also adherent to the inferior margin of the tibial plateau by the coronary ligament which may account for the increased incidence of MM tears in chronically ACL-deficient knees.

Recently, a number of studies have investigated the association between the geometry of the proximal tibia and the risk of ACL injury [34–36]; however, little information on the relationship between tibial slope and meniscal tear is available. In theory, a greater PTS will cause more anterior tibial translation under load, which may increase the forces in both the ACL and the menisci. More specifically in the lateral compartment, the increased slope may cause a rotatory moment under load [37], to which the lateral meniscus is a stabilizer [38].

Markl et al. examined the rate of meniscal tears in ACL-deficient patients and noted increased rates of meniscal tears in with medial and lateral tibial slope greater than 10° (odds ratio 2.11 for medial and 3.44 for lateral slope); however, in this small study of only 71 subjects, these findings did not reach statistical significance [36].

In the present study, the LTS was greater in the knees with LM or both meniscal tears compared to that of patients without tears, but the MTS was similar in knees with and without MM tears. In contrast, Khan et al. observed a significant association between shallower MTS and tears of the PH of the MM. They hypothesized that entrapment of the PH horn of MM within a tight medial compartment could occur as a result of the shallower MTS [39].

We suggest that PTS is one of the considerations in ACL injury to prevent secondary meniscal tears in patients with ACL injury. Increased slope, particularly in the lateral compartment is a risk factor for lateral and both meniscal tears, and when identified should prompt the clinicians to consider early ACL reconstruction to prevent further meniscal injury.

The present study has several limitations. Firstly, the retrospective design of the study is an inherent limitation, as the clinical report was sometimes imprecise concerning the description of meniscal lesions.

Furthermore, this study focused on limited risk factors. We did not evaluate factors such as activity level or lower limb alignment which may affect the severity of meniscal injury in ACL-injured patients.

Further prospective studies with greater sample sizes are needed to better understand the relationship between these parameters and tear types and sites. Biomechanical and kinematic studies are needed to further explore the association between tibial slope and meniscal tears.

4.5. CONCLUSION

Older age, male sex, increased BMI, and prolonged TFI were significant factors for the development of MM tears. An increase in the tibial slope, especially of the lateral plateau, seems to increase the risk of tear of the LM and of both menisci. Therefore, it may be suggested that the tibial slope could be one parameter to consider in ACL-injured patients for recommending early reconstruction, in order to prevent secondary meniscal tears.

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4.5.1. COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interest AE, TL, AS, and RD declare no conflict of interest. ES is the consultant for Smith & Nephew, institutional research support from Corin and Amplitude. SL is the consultant for Smith & Nephew, institutional research support from Corin and Amplitude. Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. For this type of study, formal consent is not required.

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