THE MENISCI OF THE CANINE STIFLE:
FUNCTION IN LOAD TRANSMISSION AND STABILITY

A Thesis
Presented in Partial Fulfillment of the Requirements for
The Degree of Master in Science in the
Graduate School of The Ohio State University

By
Antonio Pozzi, DMV

The Ohio State University
2005

Master’s Examination Committee:
Dr Kenneth A. Johnson, Adviser
Dr Michael P. Kowaleski
Dr Alan S. Litsky

Approved by

Adviser

Graduate Program in Veterinary Clinical Sciences
ABSTRACT

The meniscal fibrocartilages have important functions in load transmission and stability in the stifle joint. Tearing of the medial meniscus in conjunction with cranial cruciate ligament (CCL) rupture is a common cause of joint pain in animal and human patients. The recommended treatment for meniscal injuries found at the time of surgical reconstruction of the CCL deficient stifle is partial or total meniscectomy, depending upon the type of meniscal lesion. However, in cases where the meniscus is found at surgery to be grossly normal, controversy remains over the best way to prevent the development of late meniscal injury. Medial meniscal release or medial caudal pole hemimeniscectomy are often performed to prevent secondary injury to the caudal pole of the medial meniscus in the stifle joint undergoing TPLO (tibial plateau leveling osteotomy). However, both surgical procedures on the meniscus may have potential detrimental effects on load transmission and on joint stability of the stifle.

The purpose of this study was to evaluate the in vitro effect of medial meniscal release and medial caudal pole hemimeniscectomy on load transmission and stability in the stifle. Chapter 2 described the effects of medial meniscal release and medial caudal pole hemimeniscectomy on the magnitude and distribution of pressure on the articular surface
of the medial tibial condyle in the normal canine stifle, and the CCL deficient canine stifle, with and without TPLO. We found that medial meniscal release and similarly medial caudal pole hemimeniscectomy caused a significant increase in area with high pressure (> 10 MPa) in the normal and CCL deficient stifle stabilized by TPLO. We also found that CCL transection produced a significant effect on pressure distribution in the stifle without TPLO.

Chapter 3 described the effects of medial meniscal release and caudal pole hemimeniscectomy on joint stability in normal and in CCL deficient stifles with and without TPLO. Our results showed that the role of the medial meniscus in resisting tibial translation is greater in the CCL deficient stifle than in the intact stifle, suggesting a potential mechanism for the high incidence of medial meniscal tears in CCL deficient stifles. Similarly we found that the role of the medial meniscus in resisting tibial translation is greater in the sham TPLO stifle than in the TPLO stifle, suggesting that by neutralizing the tibial thrust, TPLO may be protective of the medial meniscus.

We conclude that medial meniscal release and medial caudal pole hemimeniscectomy are detrimental on joint function and should be avoided if not needed. Our results suggested that medial meniscal release may not be needed in all of the patients treated for CCL deficiency. Prospective, randomized surgical trials would be required to further evaluate the clinical importance of these findings and to give well defined criteria for meniscal surgery.
Dedicated

To my wife,
the center of my universe

To my parents,
My heroes

To Taka,
A true friend
ACKNOWLEDGMENTS

To my mentor, Dr Ken Johnson, for intellectual support, encouragement, patience and discipline which made this thesis possible.

To Don Piermattei, Erik Egger and Ron Bright, who believed in my potential and opened me a world of opportunities. I hope that I made you proud of me.

To Mike Kowaleski and Jon Dyce for stimulating discussions and for challenging me with controversial scientific questions.

To AO-VET for supporting my Residency position and my research. I also thank Ohio State University Canine Research Fund Grant for contributing with a Grant.

To Georgie Boyer and all her family for the care and love that I keep receiving.

To Ortrun Pohler for her generosity and patronage, which let me fully dedicate to this busy project.

To Stephen Birchard, Mary McLoughlin and Dan Smek, for their dedication and love for teaching. I believe that I received much more than just surgical training during the last three years.

To my resident mates. They have been my companions of this adventure, and I share with them my successes.
To Tim Vojt and Marc Hardman for their ability to transform my ideas in feelings on paper and for doing this always with a smile.
VITA

Born
February 4, 1971

1997
Dottore in medicina veterinaria (D.M.V.)
Universita' di Medicina Veterinaria di Milano
Milano, Italia

1997-2000
General practicioner with emphasis on small animal surgery and endoscopy

2000-2001
Externship in specialty practice with emphasis on small animal orthopedic surgery and soft tissue surgery

2001-2002
Internship – Small Animal Medicine/Surgery
The Ohio State University, Columbus, Ohio
2002-2005 Residency in Small Animal Surgery, The Ohio State University, Columbus, Ohio

PUBLICATIONS


FIELDS OF STUDY

Major Field: Veterinary Clinical Sciences
Specific Field: Veterinary Small Animal Surgery
# TABLE OF CONTENTS

| Abstract | ................................................................. | ii |
| Dedication | .......................................................... | iv |
| Acknowledgments | ................................................ | v |
| Vita | .............................................................. | vii |
| List of Tables | .................................................. | xiii |
| List of Graphs | .................................................. | xiv |
| List of Figures | .................................................. | xv |

## Chapters:

1. Introduction ................................................................. 1
   - History of meniscal research ........................................... 1
   - Stifle ........................................................................... 4
     - Anatomy ..................................................................... 4
     - Biomechanics ............................................................ 9
   - Stifle meniscus ............................................................ 10
     - Gross anatomy and ligaments .................................... 10
Vascular anatomy ................................................................. 13

Neuroanatomy ........................................................................ 14

Ultrastructure and composition of the normal meniscus ............ 14

Meniscal physiology ............................................................. 17

Load transmission and shock absorption .................................. 19

Joint stability ......................................................................... 22

Meniscal pathology ............................................................... 24

Epidemiology and mechanism of meniscal tear ......................... 24

Histopathology of meniscal tear ............................................ 26

Meniscal healing, regeneration, and remodeling ....................... 27

Mechanism of articular cartilage degeneration following meniscal
tear and meniscectomy .......................................................... 28

Diagnosis of meniscal pathology ............................................ 30

Treatment of meniscal pathology ............................................ 32

Arthrotomy .......................................................................... 34

Arthroscopy .......................................................................... 36

Medial meniscal release ....................................................... 37

Medial caudal pole hemi-meniscectomy ................................ 40

Total meniscectomy .............................................................. 42

Partial meniscectomy ........................................................... 43

Meniscal repair and replacement in human patients .................. 46

2. In vitro evaluation of the role of the medial meniscus in load distribution in the canine
stifle ....................................................................................... 49
Introduction ................................................................................................................. 49
Material and methods .................................................................................................. 51
Materials ......................................................................................................................... 51
In vitro limb loading ....................................................................................................... 51
Prescale pressure sensitive film ..................................................................................... 53
Experiment 1-Meniscal disruption in normal joints ....................................................... 55
Experiment 2-Meniscal disruption and TPLO in cranial cruciate ligament deficient joints ........................................................................................................... 55
Quantification of Prescale Pressure Sensitive Film ........................................................... 57
Statistical analysis ........................................................................................................... 59
Experiment 1-Meniscal disruption in normal joints ....................................................... 59
Experiment 2-Meniscal disruption and TPLO in cranial cruciate ligament deficient joints ........................................................................................................... 60
Results ........................................................................................................................... 60
Experiment 1-Meniscal disruption in normal joint .......................................................... 60
Experiment 2-Meniscal disruption and TPLO in cranial cruciate ligament deficient joints ........................................................................................................... 64
Discussion ....................................................................................................................... 68
3. In vitro evaluation of the role of the medial meniscus in joint stability in the canine stifle ........................................................................................................ 73
Introduction .................................................................................................................... 73
Material and methods .................................................................................................... 75
In vitro limb loading..............................................................75

Experiment 1 – Effect of medial meniscal release on tibial translation in normal and cruciate deficient stifles.................................80

Experiment 2 - Effect of medial meniscal release on tibial translation in the cruciate deficient stifle after TPLO.................................82

Radiographic measurement of cranial tibial translation and displacement of the caudal pole of the medial meniscus.................................84

Statistical analysis........................................................................85

Results........................................................................................86

Experiment 1 – Effect of medial meniscal release on tibial translation in normal and cruciate deficient stifles.................................86

Experiment 2 - Effect of medial meniscal release on tibial translation in the cruciate deficient stifle after tibial plateau leveling osteotomy......91

Discussion...................................................................................96

4. Conclusion ..............................................................................100

Bibliography....................................................................................104
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Distribution of load transmission in normal stifle joints: summary of percent of area with measured ranges of pressure recorded after each treatment (Mean ± SD)</td>
<td>63</td>
</tr>
<tr>
<td>2.2</td>
<td>Distribution of load transmission in cranial cruciate ligament deficient stifle joints with and without TPLO: summary of percent of area with peak pressure (&gt;10 MPA) recorded after each treatment (Mean ± SD)</td>
<td>66</td>
</tr>
<tr>
<td>3.1</td>
<td>Tibial Translation in Normal and Cranial Cruciate Deficient Canine Stifles (mean ± SD)</td>
<td>88</td>
</tr>
<tr>
<td>3.2</td>
<td>Displacement of the Caudal Pole of the Medial Meniscus after Medial Meniscal Release in Normal and Cruciate Deficient Stifles (mean ± SD)</td>
<td>90</td>
</tr>
<tr>
<td>3.3</td>
<td>Tibial Translation in Normal and Cranial Cruciate Deficient Canine Stifles (mean ± SD)</td>
<td>93</td>
</tr>
<tr>
<td>3.4</td>
<td>Displacement of the Caudal Pole of the Medial Meniscus after Medial Meniscal Release in Cruciate Deficient Stifles with and without TPLO (mean ± SD)</td>
<td>95</td>
</tr>
</tbody>
</table>
LIST OF GRAPHS

<table>
<thead>
<tr>
<th>Graph.</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Mean ± SD percent of area with each pressure range in the intact medial meniscus, medial meniscal release and medial caudal pole hemimeniscectomy groups.</td>
</tr>
<tr>
<td>2.2</td>
<td>Mean ± SD percent of area with pressure higher than 10 Mpa in the intact medial meniscus and following CCL transection, medial meniscal release and medial caudal pole hemimeniscectomy in the TPLO and SHAM TPLO groups.</td>
</tr>
<tr>
<td>3.1</td>
<td>Effect of medial meniscal release and medial caudal pole hemimeniscectomy on tibial translation in stifles with intact or a transected CCL.</td>
</tr>
<tr>
<td>3.2</td>
<td>Displacement of the Caudal Pole of the Medial Meniscus after Medial Meniscal Release in Normal and Cruciate Deficient Stifles (mean ± SD).</td>
</tr>
<tr>
<td>3.3</td>
<td>Effect of medial meniscal release and medial caudal pole hemimeniscectomy on tibial translation in stifles with TPLO or SHAM (A).</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 A</td>
<td>Tibial plateau leveling osteotomy (TPLO)</td>
</tr>
<tr>
<td>1.1 B</td>
<td>A clinical case treated by TPLO</td>
</tr>
<tr>
<td>1.2</td>
<td>Planes of motion in the femoro-tibial</td>
</tr>
<tr>
<td>1.3 A</td>
<td>Measurement of tibial plateau angle</td>
</tr>
<tr>
<td>1.3 B</td>
<td>Example of steep tibial plateau angle of 55°</td>
</tr>
<tr>
<td>1.4</td>
<td>Caudal and cranial view of the canine stifle</td>
</tr>
<tr>
<td>1.5</td>
<td>Rolling and gliding motion of the femoral joint</td>
</tr>
<tr>
<td>1.6</td>
<td>Tibial condyles, lateral and medial menisci and corresponding ligament</td>
</tr>
<tr>
<td>1.7</td>
<td>Pressure distributions on the tibial surfaces in human knees with an intact meniscus, with a bucket handle simulation, with a partial and a total menisectomy</td>
</tr>
<tr>
<td>1.8</td>
<td>Classification of meniscal tear</td>
</tr>
<tr>
<td>1.9</td>
<td>Articular cartilage degeneration following medial caudal pole hemimeniscectomy (A) and medial total meniscectomy (B)</td>
</tr>
<tr>
<td>1.10</td>
<td>Stifle effusion and degenerative joint disease</td>
</tr>
</tbody>
</table>
1.11 CT Arthrogram of stifle. A: sagittal reconstruction of normal stifle; B: transverse reconstruction of normal stifle; C: sagittal reconstruction of stifle with a medial meniscal tear; D: transverse reconstruction of stifle with a medial meniscal tear.

1.12 Cranio-medial (A) and caudo-medial (B) approach to the stifle.

1.13 Stifle arthroscopy: A: intact medial meniscus; B: meniscal tear.

1.14 Mid body meniscal release through a caudo-medial approach.

1.15A Mid body meniscal release.

1.15B Meniscal release at the caudal menisco-tibial ligament.

1.16 Proposed mechanism for displacement of the caudal pole of the meniscus following medial meniscal release.

1.17 Caudal pole hemimeniscectomy.

1.18 Total meniscectomy.

1.19 Partial meniscectomy.

2.1 In vitro limb loading under material testing machine.

2.2 A: the transfer sheet is A layer and the developer sheet is C layer; B: calibration curve.

2.3 Insertion of the Prescale film through a caudo-medial approach.

2.4 Normal stifle (intact CCL).

2.5 Stifle with TPLO (A) and with SHAM TPLO (B).

2.6 Oval template marked on a Prescale film.

2.7 Pressure distribution across the join with A: intact meniscus, B: medial meniscal release and C: medial caudal pole hemimeniscectomy.
2.8 Caudal shift of the area of higher pressure in B (medial meniscal release) compared to A (intact meniscus). Pressure sensitive film stained following medial meniscal release illustrates the caudal location of the area of high pressure on the medial tibial plateau. .................................................................64

2.9 Pressure distribution across the joint. A:TPLO stifle with intact CCL and intact meniscus ..............................................................................................................72

3.1 Radiographic measurements ........................................................................77

3.2 In vitro limb loading in the custom made limb press ........................................78

3.3 Intact and transected CCL ........................................................................81

3.4 TPLO and SHAM TPLO ........................................................................83

3.5 Radiographs taken before treatment (A and D) and after medial meniscal release (B and E), and medial caudal pole hemimeniscectomy (C and F) in the intact and deficient CCL stifle ........................................................................89

3.6 Radiographs taken before treatment (A and D) and after medial meniscal release (B and E), and medial caudal pole hemimeniscectomy (C and F) in the CCL deficient stifle treated by TPLO or untreated (SHAM) .........................94
CHAPTER 1

INTRODUCTION

History of meniscal research

Our understanding of the structure and function of the menisci has evolved greatly during the last two centuries. The menisci were first described in 1897 by Sutton as functionless remains of leg muscle origins. Acceptance of this view as fact was implied with the practice of the surgical concept that meniscectomy was a benign procedure involving the removal of a diseased, functionless redundant structure. In the early 20th century an increasing number of anatomists suggested that menisci were a functionally important component of the knee joint. In 1917 Sisson suggested that menisci helped to prevent concussion and in 1932 MacConaill proposed that they enhance lubrication of the joint. In 1936 King concluded that the menisci served to protect the articular cartilage from degeneration, based on his landmark experiments involving partial and total meniscectomy in dogs. In 1948 Fairbank was probably the first to suggest a direct load-bearing role for the menisci. In a classic study he showed an increased incidence of degenerative changes of the articular surface of the knee after meniscectomy due to the loss of load-bearing function of the menisci.
In 1936 King also described the contribution of the menisci to joint stability by deepening the tibial socket and increasing the congruity of the femoro-tibial joint.\textsuperscript{4,5} In 1965 Huckell suggested that total meniscectomy caused joint laxity, but no clinical effects. Later Johnson and McGinty confirmed that the menisci have a stabilizing effect and that preserving the residual rim by doing a partial meniscectomy had benefits for the ultimate stability of the femoro-tibial joint.\textsuperscript{6,7}

Since the reports of King and Fairbank, the results of a large number of experimental and clinical studies on menisci supported the need for a more conservative approach to the treatment of meniscal injury.\textsuperscript{6,8-10} Although this new realization of the critical role of the menisci in normal knee function has led to increased efforts to preserve injured menisci in human patients whenever possible, meniscal procedures on grossly normal menisci are still commonly performed in dogs.\textsuperscript{11-13}

The first clinical cases of meniscal injuries in dogs were described in 1926 by Carlin, while the first clinical report of meniscectomy was from the Royal Veterinary College in Sweden in 1937.\textsuperscript{14,15} Subsequent to these initial reports, Flo described a larger series of dogs with meniscal injuries and their classification, together with a description of a medial meniscectomy technique.\textsuperscript{16-18}

Simultaneously, improvements in the management of meniscal injury coincided with improvements in the surgical treatment for cranial cruciate ligament (CCL) rupture and numerous techniques for ruptured CCL repair were described.\textsuperscript{19-30} In 1952 Paatsama reported on the replacement of the CCL by a fascial strip.\textsuperscript{31} In 1967 Strande expanded this work on intracapsular techniques with the use of the middle third of the patella tendon. He also reported frequent damage to the caudal horn of the medial meniscus in
conjunction with CCL rupture. De Angelis and other authors described the results of extracapsular procedures with variable success. The plethora of procedures is proof that the experience in dogs is similar to humans, that the surgical treatment of the CCL rupture is better than conservative treatment, but it is inconsistent and does not provide for normal joint function post-operatively.

Figure 1.1: A: TPLO; B: a clinical case treated by TPLO.
In an attempt to overcome some of the limitations of intra- and extra-articular techniques for ruptured CCL repair, a new approach to CCL rupture, the TPLO procedure, was introduced in 1993 (see Fig. 1.1). While the traditional intra- and extra-articular techniques for CCL rupture repair aimed at restoring the stifle stability throughout the joint range of motion, the TPLO provides functional stifle stability during the stance phase of the gait by eliminating the cranial tibial thrust force. It has been theorized that meniscal release is necessary while performing TPLO to prevent damage to the caudal horn of the medial meniscus. To date, however, the effect of meniscal release, with or without TPLO, on the biomechanics of the stifle has not been investigated.

Stifle

Anatomy

The stifle is a complex, diarthrodial, synovial joint that allows motion in three planes (see Fig 1.2). The round femoral condyles articulate with the flat tibial condyles with a range of motion that goes from 125° in extension to 155° in flexion. Unlike the hip, the bony congruency between the femoral condyle and the tibial plateau adds little to the stability of the stifle. Rather, the strong cruciate and collateral ligaments primarily, and the menisci, the capsule and the musculature secondarily, constitute the stabilizers of the stifle. These structures and muscles around the knee constitute a complex biomechanical system in which the tibia can move with respect to the femur in many planes and support high loads.
The complexity of the normal motion is directly related to the structure and functions of the anatomical components that form the joint. The intercondylar fossa in dogs consists of a cranial outlet, intercondylar shelf, caudal arch, caudal outlet, a medial wall, and a lateral wall. Fitch et al reported that the normal cranial outlet is bell-shape and, in mixed-breed dogs its width measured 5.8 mm cranially, 8.1 mm centrally, and 10.3 mm caudally. The intercondylar fossa is oriented 12 degrees from the dorsal plane of the femoral diaphysis and obliqued 7 degrees, proximolateral to distomedial, in the sagittal plane.\textsuperscript{43}

The tibial plateau is the proximal articular surface of the tibia, composed of the lateral and medial tibial condyles. The tibial plateau slope is defined as the angle between
a line representing the plane of the tibial plateau and a line in place of the functional axis of the tibia (see Fig. 1.3). Steep tibial plateau angles have been associated with an increased incidence of cranial cruciate ligament rupture (see Fig. 1.3).\textsuperscript{39,44,45}

The popliteus muscle originates from the lateral femoral condyle and inserts on the medial proximal aspect of the tibia. Biomechanical studies of human knees have shown that the popliteus appears to act as a dynamic guidance system for monitoring and controlling subtle transverse- and frontal-plane knee joint movements, controlling anterior-posterior lateral meniscus movement, unlocking and internally rotating the knee joint during flexion initiation, preventing forward femoral dislocation on the tibia during flexed-knee stance, and providing for postural equilibrium adjustments during standing.\textsuperscript{46} Enhanced popliteus function may help to prevent athletic knee joint injuries and facilitate recovery during rehabilitation by assisting the primary sagittal plane dynamic knee joint stabilization provided by the quadriceps femoris, hamstrings, and gastrocnemius.\textsuperscript{46}

The cruciate ligaments, located between the femur and the tibia, limit internal rotation of the tibia, hyperextension of the stifle and tibial translation.\textsuperscript{47} Morphologically the canine cranial cruciate ligament can be divided into cranio-medial and caudo-lateral components which perform reciprocal functions at all angles of flexion of the stifle joint. Histologically the main constituents of these two components are bundles of longitudinally orientated collagen fibers.\textsuperscript{47,48} The CCL originates from the medial aspect of the lateral femoral condyle and inserts to the cranio-medial aspect of the tibial plateau. The caudal cruciate ligament originates from the lateral aspect of the femoral condyles and inserts to the caudo-lateral tibial plateau (see Fig. 1.4).
Figure 1.3: A: measurement of tibial plateau angle; B: example of tibial plateau angle of 27°; (C) example of steep tibial plateau angle (55°)
The collateral ligaments extend respectively from the lateral and medial femoral condyle to the lateral and medial tibial condyles. The medial collateral ligament is taut in extension, with only the caudal portion of the ligament becoming lax in flexion. The lateral collateral ligament is also taut in extension; however, its entire bulk becomes lax as the joint is flexed. In extension, the ligaments are primary restraints preventing varus and valgus angulation, and they limit internal and external rotation of the tibia. In flexion, the cranial portion of the medial collateral ligament remains taut and prevents external rotation of the tibia, whereas the relaxation of the lateral collateral ligament allows the tibia to rotate internally, with further rotation limited by the cruciate ligaments.\textsuperscript{49}

\textbf{Figure 1.4:} caudal and cranial view of the canine stifle.
Biomechanics

Biomechanically, the stifle is perhaps the most complex joint in the body. The primary movement of the stifle is flexion-extension. This movement, unlike a simple hinge, consists of a varying mixture of rolling and gliding (see Fig. 1.5). By examination of these two movements in isolation, the need for a complex motion becomes readily apparent if full flexion is to occur.

![Diagram of the femoro-tibial joint showing rolling and gliding motion](image)

**Fig. 1.5:** the rolling and gliding motion of the femoro-tibial joint.
If only rolling (flexion-extension rotation without cranio-caudal translation) occurred, the femoral condyle would roll off the tibial plateau long before full flexion was completed. On the other hand, if gliding (cranio-caudal translation without flexion-extension rotation) were the principle movement, the caudal margin of the femur would strike the caudal tibial plateau before the completion of full flexion. Therefore, for a normal range of motion to occur, a mixture of rolling and gliding must occur (see Fig. 1.5).  

**Stifle meniscus**

**Gross anatomy and ligaments**

Menisci are C-shaped disks of fibrocartilage located between the condyles of the femur and the tibia (see Fig. 1.6). Embryologically the menisci begin as a condensation of intermediate layer of mesenchymal tissue and are well defined structures by the eighth week of development in the human fetus. During the development, collagen fibers increase in number and gradually orientate in circumferential bundles, influenced partially by the joint motion. The blood supply initially seen across the whole meniscus, reduces to the peripheral third of the meniscus by mid-adolescence in humans.
The menisci play an important role in the function of the stifle, a diarthrodial joint with articulating surfaces of highly dissimilar geometry.\textsuperscript{55,56} The congruity between femur and tibia is improved by the concave articular surface created by the menisci.\textsuperscript{53,57,58} The peripheral border of each meniscus is thick, convex, and attached to the inside of the joint capsule; the axial border tapers to a thin free edge. The proximal surfaces of
the menisci are concave and in contact with the femur condyles while the distal surfaces of the menisci are flat and rest on the head of the tibia.

The menisci are a functional extension of the tibia and are held in place by ligaments and soft tissue attachments. The cranial horn of the medial meniscus is attached to the tibial plateau in the area of the cranial intercondylar fossa in front of the CCL by the cranial menisco-tibial ligament. The caudal horn is firmly attached to the caudal intercondylar fossa of the tibia between the attachments of the lateral meniscus and the caudal cruciate ligament by the caudal menisco-tibial ligament (see Fig. 1.4). The periphery of the medial meniscus is firmly attached to the joint capsule from the cranial meniscal-tibial ligament caudally to the medial collateral ligament. At this level a bursa prevents a menisco-tibial capsular attachment. The proximal peripheral border of the caudal body the medial meniscus has some capsular attachments. The lateral meniscus is almost circular and covers a larger area of the tibial condyle than the medial meniscus. The cranial horn of the lateral meniscus is attached to the tibia cranial to the intercondylar eminence and behind the attachment of the CCL, by the cranial menisco-tibial ligament. The caudal horn is attached to the caudal intercondylar fossa of the tibia in front of the caudal cruciate ligament by a poorly defined caudal menisco-tibial ligament (see Fig. 1.4). The caudal horn of the lateral meniscus is also firmly attached to the medial surface of the medial femoral condyle by the menisco-femoral ligament. Attachments of the lateral meniscus to the joint capsule are less extensive than the medial meniscus because of the presence of the popliteus tendon. The menisco-tibial capsule along the course of the popliteal tendon forms a ventral sheath in which the tendon glides. Caudal to the popliteal tendon there is not any tibial-capsular attachment to the meniscus except at the
level of the popliteal notch. The intermeniscal ligament is located between the cranial horns of the lateral and medial menisci.

Vascular anatomy

The blood supply to the menisci originates from the lateral and medial genicular arteries. Branches from these vessels form a perimeniscal plexus which is found within the joint capsule of the stifle joint. The perimeniscal capillary plexus supplies the peripheral border of the menisci through its attachments to the joint capsule. The radial branches, originating from the predominant perimeniscal circumferential vessels, penetrate about 30% of the width of the medial meniscus and about 25% of the width of the lateral meniscus. The middle genicular artery also gives rise to smaller vessels that enter the meniscal horns for a short distance. A small portion of vascular synovial tissue extends shortly over the femoral and tibial articular surfaces of the menisci, but it does not give rise to vessels that penetrate into the menisci.

Although the peripheral portion of the menisci is vascularized, most of the meniscus is avascular and must rely to a large degree on synovial sources of nutrition. Alternative mechanisms for nutrition are diffusion or mechanical pumping of synovial fluid from compression of the tissue during stifle motion. Regional differences in transport of synovial fluid may explain the finding that highest incidence of degenerative changes is within the central core region of the meniscus in human patients.
Neuroanatomy

The nerve supply of the menisci has been extensively studied in humans and animals.\textsuperscript{65,66} Myelinated and unmyelinated fibers distribute to the peripheral part of the meniscus while the most richly innervated are the cranial and caudal horns. Studies in human specimens have showed that there are a high number of mechanoreceptors within the medial meniscus.\textsuperscript{67} These findings suggested that the medial meniscus may have a proprioceptive function. The mechanoreceptors located in the meniscal horns would be activated during extreme flexion and extension of the stifle, providing the central nervous system with information regarding joint position.\textsuperscript{68}

Ultrastructure and composition of the normal menisci

The menisci are fibrocartilaginous structures with macromolecular components (e.g., collagen, proteoglycans), cells and predominantly water. The water content of the meniscus is about 75%. Meniscal tissue contains different molecular species of collagen, but type I is the predominant type, accounting for more than 90% of the total collagen present. Collagen type II, III, V and VI have been shown to be present only in small amounts and type II fibers are more prominent on the surface layers.\textsuperscript{69} Collagen fibers have a definite pattern of orientation within the meniscus that can be related to the mechanical function and to the ways in which tears develop.\textsuperscript{70} In the surface layer, the fibers of collagen are roughly parallel to the surface of the tissue and are randomly dispersed in the plane of the surface; deeper down, in the bulk of the tissue, they tend to be oriented circumferentially (around the curve of each crescent-shaped meniscus), and run more or less continuously from the anterior attachment to the posterior attachment.
site. Not all the fibers of the bulk tissue are oriented circumferentially; some point out
toward the surface layer, perhaps to ensure that the surface is mechanically linked to the
bulk. Between these large circumferentially arranged collagen fiber bundles are the
smaller “tie fibers” that run radially from the periphery to the inner edge. The orientation
of the collagen fibrils in the meniscus is consistent with its having to withstand
compression forces between femur and tibia. At the concave femoro-meniscal surface the
force originating from weight bearing has a vertical and a radial component. To balance
the radial component of the femoro-meniscal force, internal forces must be developed
along the circumferentially arranged collagen fiber bundles. These forces are aligned
tangent to the collagen fibers.

Collagen can reinforce a tissue provided that deformation of the tissue tends to
stretch its fibrils; the force developed in the stretched fibrils opposes the applied stress.\textsuperscript{71}
The load applied to the meniscus would be expected to stretch the circumferentially
oriented collagen fibrils that, therefore, are able to reinforce the tissue. The hypothesis
that compression generates a circumferential strain in the meniscus was proposed by
Fairbank and further described by Shrive.\textsuperscript{5,72} In their models a compression perpendicular
to the concave surface of the meniscus, represented as a ring, would generate a tensile
stress across its entire cross-section.

In addition to collagen, elastin is present in small amounts in the meniscus. It has
been suggested that the function of the elastic fibers of the meniscus is to help it to
recover its original dimension when the applied load in a given direction decreases.\textsuperscript{73}
Because the direction of joint loading is continually changing during weight bearing,
rapid recovery of shape is important for maintaining joint congruity.
Proteoglycans are important components of the menisci. Proteoglycans are critically important in the maintenance of hydration, firmness and elasticity. They are composed of a large protein core to which many chondroitin sulfate, keratan sulfate and other glycosaminoglycan chains are attached. The overall proteoglycan content of the meniscus is relatively small, but this can vary with the age of the tissue. The large aggregating type of proteoglycan, called high buoyant density proteoglycan, is the major type seen in the meniscus and is similar to which is present in hyaline cartilage. Another group of molecules is called low buoyant density proteoglycans, and includes smaller molecules that do not aggregate with hyaluronate, but are enriched in keratan sulfate. The aggregating proteoglycans have been extensively studied and are known to contribute most significantly to the material properties of cartilage.\textsuperscript{74} The function of aggregation appears to be to immobilize the proteoglycans within the collagen network. The chondroitin sulfate and keratin sulfate chains of the proteoglycan contribute to important functions of these molecules. They are composed of disaccharide units that become dissociated and charged in the interstitium of the tissue. This causes a high concentration of extra ions and an increased interstitial osmotic pressure. These characteristics are responsible for the compressive stiffness, tissue hydration and swelling, low permeability and shear stiffness of the meniscus. The degree of hydration in cartilaginous tissue depends on the swelling pressure and tensile stiffness of the restraining collagen meshwork surrounding the trapped the proteoglycans. Thus, a tissue with a high proteoglycan/collagen ratio will tend to swell more than a tissue with a low ratio. Also a tissue with a damaged collagen meshwork will gain water over and above its normal
physiologic state. A reduction of hydration would result from proteoglycan loss from the matrix during degeneration.

Profound changes occur in meniscal glycosaminoglycans in human osteoarthritis and in spontaneous and experimental canine osteoarthritis.\textsuperscript{75-77} After experimental surgical transection of the CCL in canine stifles, the meniscus shows decreased content of chondroitin sulfate and keratin sulfate of greater than 30\% and 50\% of control values, respectively, in the early phases of the postoperative period \textsuperscript{77}. In late natural and experimental animal models of osteoarthritis, however, there is an increase in content by more than 70\% of control values of both of these glycosaminoglycans. A similar early decrease in glycosaminoglycan concentration and late increase was also reported in human knees. These changes may be due to accelerated loss of keratan sulfate-rich proteoglycans or to faster synthesis of chondroitin sulfate-rich proteoglycans. This may support the use of oral glucosamine in patients with a meniscal tear and osteoarthritis.\textsuperscript{78}

**Meniscal physiology**

The menisci were once considered ancillary structures of the femoro-tibial joint, but are now considered integral components in the complex biomechanics of the stifle.\textsuperscript{1, 5, 79, 80} The menisci have important biomechanical functions in the femoro-tibial joint such as load bearing, load distribution, shock absorption and joint stability.\textsuperscript{5, 53, 55, 57, 58, 60, 61, 72, 73, 80-95} Although the complexity of their functions has still to be completely understood, the shape and construct of the menisci have long been understood to be related to their role in
The congruity between femur and tibia is improved by the concave articular surface created by the menisci.\textsuperscript{53, 57, 58, 57, 59-61}

The normal function of a diarthrodial joint depends on many factors, two of which are stability and uniform distribution of load across the joint. These two factors depend on the geometry and on the material properties of the articulating surfaces. The knee menisci participate in load support and stability through the wide range of motion of the knee joint and provide primarily mechanical function to a complex system made of tissues with different properties. Meniscus material properties and function depend on its composition and ultrastructural organization. However, its composition is also affected by the mechanical stresses that are applied to it. An example of different loading configurations can be referred to three major connective tissues of the body. For tendon and ligaments the collagen fibers bundles are clearly aligned parallel to the forces and stresses that these tissues must carry. For articular cartilage the forces and stresses acting on the tissue are multidirectional and more complex; for the meniscus its wedge shape and its near frictionless surface causes the vertical loading to develop a radial extrusive force. These three tissues clearly have three different structure-function configurations. The mechanical function of the meniscus depends not only on its unique geometric form, but also on its biphasic visco-elastic properties, which in turn depend on the properties and interactions of the tissue’s macromolecular components (e.g. collagen, proteoglycans) and water. For both meniscus and articular cartilage the compressive visco-elastic properties are determined by the frictional drag of fluid flowing through the matrix in response to the mechanical stresses.
Load transmission and shock absorption

The role of the menisci as load bearing elements have been already studied in depth in human and animals models. Several studies have shown that meniscectomy causes an immediate, acute increase in stifle contact peak pressure and that these changes in stress distribution cause remodeling of bone and soft tissue. Ahmed and Burke reported that removal of the medial meniscus caused a reduction in the contact area by 50-70% and a marked increase in peak pressure in the human knee (see Fig.1.7). Krause showed that canine menisci transmit 65% of the weight bearing and that a two-fold increase in compressive deformation of cartilage and subchondral bone occurred after meniscectomy. Shrive reported that radial transection of the porcine and human meniscus was equivalent to meniscectomy in terms of load-bearing, suggesting the loss of hoop tension was responsible for high and non-uniform pressure distribution.

The menisci distribute the load over a larger surface and help lower the stress of the cartilage, protecting against mechanical damage to both the chondrocytes and extracellular matrix. Contact stress originate from an object applied with a force (F) to an area (A) \( \sigma = \frac{F}{A} \). Either a decrease in area or an increase in force, may increase contact stress. The menisci also prevent contact between the tibial and femoral cartilage surfaces when no compressive forces are applied, by the so called “spacer effect”. The contact area is large due to the menisci and thus the average contact stress acting between bones is reduced. This means that the menisci help lowering the stress on the cartilage and protect against mechanical damage to chondrocytes and extracellular matrix.
Figure 1.7: pressure distributions on the tibial surfaces in human knees with an intact meniscus, with a bucket handle simulation, with a partial and a total meniscectomy; gradations in colours blue, yellow, orange and red represent indicate increasing pressure from 0.35 to 2.75 MPa (from Ahmed A.M. et al. 81)
Different models showed that meniscus absorbs energy by undergoing elongation as a load is being applied on the knee. As the joint compresses, the wedge shaped meniscus extrudes peripherally and its circumferentially oriented collagen fibers elongate. The force required to restrain the radial extrusion of the meniscus derives from the large tensile hoop stress developed within the strong circumferential collagen fibers bundles from the extrusive effect. These hoop forces are transmitted to the tibia through the strong anterior and posterior attachments of the menisci. These circumferential forces would act in the same way as metal hoops placed around a pressurized wooden barrel. The tension in the hoops keeps the wooden staves in place when the barrel is full.

Other factors that influence meniscal shock absorption are its mechanical properties. The combination of low compressive stiffness and low permeability suggests that the menisci, as structures, should function as highly efficient shock absorbers per unit mass. Most of the vertical force acting on the knee most likely is absorbed by the menisci because their combined mass is much greater than that of the articular cartilage. Also the low stiffness aids in load distribution by being more deformable.

The load transmission and shock absorption functions of the menisci are vital for normal metabolism of the articular cartilage. If the protective function of the menisci is lost, the increased and repetitive stress caused by the axial load of the joint may cause mechanical and biochemical damage to the cartilage. The link between meniscal damage or meniscectomy and osteoarthritis is not well understood. It has been proposed that compression of the cartilage at physiological strains serves as a signal to modulate chondrocyte responses, while prolonged compression at higher strains may be responsible for tissue and cell damage. Radin et al reported that failure of a damaged or
resected meniscus to attenuate peak dynamic force may predispose to subchondral bone stiffening and consequently osteoarthritis.\textsuperscript{107,108} Clements reported that repetitive compressive loading with peak stress ranging between 3.5 and 14 MPa caused an immediate dose-related increase in collagen denaturation in bovine articular cartilage.\textsuperscript{83} Furthermore, there is a body of clinical literature that suggests that surgical removal of the medial meniscus constitutes a risk factor for the later appearance of joint cartilage changes.\textsuperscript{8,9,109}

In the first part of our study we quantified the pressure distribution in the medial compartment of the tibial plateau in the canine stifle. Our purpose was to determine if surgical procedures on an intact medial meniscus could be detrimental to load distribution across the joint.

\textbf{Joint stability}

After transection of the CCL, cranial tibial displacement is controlled by straining the collateral ligaments and joint capsule, and by the congruency effect related to surface geometry and compression or buttressing of the menisci as contact force is applied.\textsuperscript{58,80,94} By filling the void between the curved femoral condyle and the flat tibial plateau, the medial meniscus improves joint congruity and ultimately increases contact area and stability.\textsuperscript{57} The menisci have been considered as stabilizing elements in the human and animal femoro-tibial joint.\textsuperscript{58,60,80,92-95,110-113}

In 1980 Butler and coworkers evaluated the rank order importance of the knee structures in contributing to the anterior-posterior stability of the human knee.\textsuperscript{114} The anterior cruciate ligament was found to be the prime static restraint to anterior translation
of the tibia on the femur. The posterior cranial cruciate ligament was determined to be the main static restraint to posterior translation. The rest of the ligamentous or capsular structures did not contribute more than 25% to the overall knee stability. This study was important because for the first time a rank order of importance of restraining articular structures was described, introducing the concept of primary and secondary restraints. In 1982 Levy and coworkers evaluated the effect of meniscectomy on knee motion before and after transection of the anterior cruciate ligament in cadaveric human knees. Levy found that as anteriorly directed force was applied to the tibiae of anterior cruciate ligament deficient knees, the medial meniscus acted as a wedge between the femur and the advancing tibia, restraining the tibia from further displacement. From this study it was concluded that anterior tibial translation was greater in knees that lacked both a medial meniscus and an anterior cruciate ligament than in knees with an isolated anterior cruciate ligament rupture. Fukubayashi et al found similar results to Levy, but also found that meniscectomy had a significant effect on the coupled internal rotation concomitant to the tibial translation. In 1986 Shoemaker and Markolf found that progressive meniscectomy caused the tibia to subluxate forward, suggesting that loaded menisci do resist anterior subluxation in knees lacking an anterior cruciate ligament. In particular they concluded that the posterior horn of the medial meniscus was responsible for resisting anterior translation of the tibia.

There are some major anatomical difference between dogs and humans in the femoro-tibial joint. During stance phase, the angle of the canine stifle is of 135° and of the human knee is about 180°. In both species the tibial plateau is not perpendicular to the tibial shaft axis but has a caudal slope. In humans this slope is 5° to 10° and in dogs is
These differences may play a role in the magnitude of forces acting on the femoro-tibial joint and its biomechanics.\textsuperscript{39,119}

Despite anatomical differences, the canine medial meniscus may also play an important role in stability in the canine stifle. The caudal pole of the medial meniscus may encounter shear during femoro-tibial subluxation in the CCL deficient stifle. This could potentially explain the high rate of secondary medial meniscal tears in dogs with CCL deficiency.\textsuperscript{120,121} Studying the contribution of the medial meniscus to the canine stifle stability is one of the purposes of this study.

\textbf{Meniscal pathology}

\textbf{Epidemiology and mechanism of meniscal tear}

Tearing of the medial meniscus in conjunction with CCL is a common cause of joint pain in people and animals.\textsuperscript{17,18,102,120,122-126} Meniscal injury in the dog is most commonly associated with ligament injury of the stifle joint. The reported incidence varies from 50 to 90\%.\textsuperscript{17,18,35,94,127} The mechanism of injury can be explained with the anatomical features of the medial meniscus. The medial meniscus is firmly attached to the tibia by the medial collateral ligament, the synovium, and the meniscal ligaments. As a result, during drawer movement and weight bearing the caudal pole may become entrapped between the femoral and the tibial condyle and therefore may tear due to the shear stress applied on the longitudinal and radial fibers.

At the ultrastructural level, the organization of the collagen fibers helps defining the type of mechanical failure of the meniscus. In connective tissues, the hydrated
proteoglycans are mechanically much weaker than the collagen fibers. When these tissues are excessively stressed, the proteoglycans will begin to break first. The crack, once started, will continue to propagate as long as the stress is maintained, and will propagate in the weaker surrounding material or along the interface rather than across the stronger fibers. If compression of the meniscus produces an excessive circumferential tensile stress, the tissue will dissipate strain energy by crack propagation perpendicular to the tensile stress.

Meniscal tears have been classified into 5 different types (see Fig. 1.8). Vertical longitudinal tears: include bucket handle tears, short vertical tears and incomplete vertical tears. Incomplete vertical tears can be diagnosed only with careful probing. Bucket handle tears are the most common type of tear and may be seen as multiple tears in the same meniscus.

Oblique or flap tears: may be single or double, and include parrot beak tears. They usually start as vertical tears, become bucket handle tears, and then tear completely at either handle end and become a single or double flap.

Radial tears: more commonly occur in the lateral meniscus and they may propagate if left untreated.

Horizontal or horizontal cleavage tears: less common than other tears. Incomplete horizontal tears can be difficult to diagnose and may go undiagnosed in many cases.

Degenerative tears. These tears can be seen with any type of tear, but most commonly from delayed treatment and chronic trauma from walking on injured menisci.
Histopathology of meniscal tear

A tear is the most common abnormality encountered in a meniscus. The microscopic appearance is similar regardless of the type of tear. The round edges show proliferation of cells that look round instead of spindled. Pathologic changes may include mucoid degeneration, chondrocyte proliferation, calcification, fragmentation, tearing of collagen bundles and necrosis. Inflammation and granulation tissue are not present in tears occurring in the more central parts of the meniscus. When the peripheral part of the meniscus is also torn, hemorrhage and vascular proliferation may be evident.

Degenerative changes of the meniscus may be seen very early in the pathogenesis of the CCL deficient-stifle. Adams et al were the first to describe severe gross morphological changes of the menisci following CCL transection in dogs, including fibrillations and tears of the meniscal tissue. They also reported an early reduction in the meniscal glycosaminoglycan content of the menisci, followed by return to normal glycosaminoglycan content after 3-18 months post-injury. Jackson et al suggested that
subtle histologic changes are present in grossly normal menisci from dogs with naturally occurring rupture of the CCL.\textsuperscript{130}

**Meniscal healing, regeneration and remodeling**

Controversy exists within the orthopaedic literature regarding the ability of a meniscus or a meniscus-like tissue to regenerate after meniscectomy.\textsuperscript{132-134} A good understanding of the vascular anatomy is necessary to understand meniscal healing, regeneration and remodeling. In 1936 King published his classic experiment on meniscus healing in dogs, showing that for meniscus lesions to heal, the lesion must communicate with the peripheral blood supply.\textsuperscript{4} After an injury within the peripheral vascular zone, a fibrin clot forms that is rich in inflammatory cells, originating from the synovium or from the meniscus itself.\textsuperscript{62} Vessels from the perimeniscal capillary plexus proliferate through this fibrin “scaffold” accompanied by the proliferation of undifferentiated mesenchymal cells. Eventually the lesion is filled with a cellular, fibrovascular scar tissue that fuses the wound edges together and appears continuous with the adjacent normal meniscal fibrocartilage in case of a tear, or fill the dead space in case of meniscectomy.\textsuperscript{135} If the meniscal section or tear is in the avascular region of the meniscus, meniscal fibrochondrocytes are capable of proliferation or matrix synthesis but the mean degree of meniscal repair is less than half of that of subtotal and partial meniscectomy. Experiments in rabbit and dogs have demonstrated that after total meniscectomy there is regrowth of a structure that is similar in shape and texture to the removed meniscus.\textsuperscript{136} Fibroblasts from the synovium and capsule migrate onto the fibrin scaffold. Then the cells proliferate and synthesize a fibrous connective tissue. In about 7 months this tissue
has the histologic appearance of fibrocartilage and grossly resembles a meniscus.\textsuperscript{137} For this meniscus-like tissue to regenerate, however, the entire meniscus must be resected to expose the vascular synovial tissue, or in case of a sub-total meniscectomy the excision must extends into the vascularized periphery. Despite the resemblance of this regenerated meniscus to a normal meniscus, the functions of an intact meniscus are lost. Due to the biomechanical importance of the meniscus and the lack of functional relevance of the repaired meniscal tissue, the most conservative approach possible to meniscectomy has been recommended.

If degenerate or damaged meniscal tissue is debrided from the avascular zone (partial meniscectomy) a remodeling response is noted. The stimulus for this reparative response most likely results from an extrinsic source, such as an organized hematoma adjacent to the meniscectomy surface. This process appeared to begin with a fibrin clot which adhered to the meniscectomy surface. The organized clot was then populated by fibrocytes and eventually modulated into a fibrocartilage-like tissue. The origin of the cells is unknown and may represent a migration of cells from the synovium, a proliferation of meniscal fibrochondrocytes, or both. The remodeling process appears to be associated with the presence of a fibrin clot, presumably from residual hemarthrosis.\textsuperscript{137}

**Mechanism of articular cartilage degeneration following meniscal tear and meniscectomy**

Osteoarthritis is a progressive destructive joint disease characterized by severe deterioration of joint tissues. Since the early experiment of King in 1936, the menisci were considered important for protection of articular cartilage from degeneration.\textsuperscript{4} Since the first report from King, many authors have studied the function of the menisci, but the
link between meniscal damage or meniscectomy and osteoarthritis is not well understood yet.\textsuperscript{86, 102-106} Johnson et al. reported that medial caudal pole hemimeniscectomy causes articular cartilage degeneration similar to medial total meniscectomy, suggesting that caudal pole hemimeniscectomy is not a benign procedure (see Fig. 1.9).\textsuperscript{138}

![Fig 1.9: articular cartilage degeneration following medial caudal pole hemimeniscectomy (A) and medial total meniscectomy (B) (from Johnson et al. 138)](image)

It has been suggested that supra-normal loading of articular cartilage, such as that which occurs following meniscectomy, alters chondrocyte's proteoglycans metabolism, resulting in ultimate mechanical failure of the tissue.\textsuperscript{88, 101, 105} If medial meniscal release
has equivalent effects on load transmission as caudal pole hemimeniscectomy or total meniscectomy in dogs, it may play a role in the development of osteoarthritis in the canine stifle.

**Diagnosis of meniscal pathology**

Pre-operative and intra-operative techniques are available to assist in recognizing a damaged meniscus. Magnetic resonance imaging is used extensively for knee injuries in humans and has been described in veterinary medicine.\(^{139,140}\) Human studies report 90-94 percent sensitivity specifically diagnosing medial meniscal injuries.\(^{140}\) However, clinical examination remains a useful diagnostic tool in human orthopaedics. In 2004 Kocabey evaluated the accuracy of clinical examination and MRI evaluation in a prospective longitudinal study. He found that there was no statistical difference between MRI or clinical examination in diagnosing medial or lateral meniscal tears or ACL tears, and that a well-trained qualified surgeon could safely rely on clinical examination for diagnosing meniscal and ACL injuries.\(^{141}\) Furthermore, in 1992 Boden reported that the “high incidence of abnormal MRI findings in asymptomatic subjects underscores the danger of relying on a diagnostic test without careful correlation with clinical signs and symptoms”.\(^{142}\)

Meniscal tears are most commonly associated with CCL rupture in animals. The typical patient presenting with a meniscal tear is a large, overweight dog with a complete chronic CCL rupture, severe crepitus, effusion, and pain on palpation of the stifle joint.
Radiographic examination may help confirm the diagnosis of CCL rupture and meniscal tear by ruling out other stifle pathology and identifying characteristic osteoarthritic and soft tissue changes (see Fig. 1.10).

Fig. 1.10: stifle effusion and degenerative joint disease
In some cases the clinician may need additional information before recommending an arthrotomy or an arthroscopy. For example, a dog presenting for mild intermittent hind lameness with minimal pain and a palpably stable stifle joint may benefit from an MRI or a CT arthrogram before more invasive procedures. MRI has been used in animal patients, but is not always available to the surgeon. Another valid imaging technique is CT arthrogram (see Fig.1.11). Advantages of this technique include the ability to perform multiplanar reconstructions to evaluate the continuity of the cranial and caudal cruciate ligaments and menisci as well as its increasing availability in university and private centers.

**Treatment of meniscal pathology**

In human orthopaedics in the late 1960s and early 1970s, it was recognized that torn menisci were a source of clinical pain and that the standard treatment for any proven meniscal tear was open total meniscectomy. The short term results with this treatment were satisfactory. During 1970s and 1980s, numerous research groups began looking at the biomechanical consequences of meniscectomy, stimulated by the increasing evidence of adverse late clinical sequelae resulting from total meniscectomy.

The results of these studies triggered the adoption of a more conservative treatment of meniscal tear, with the hope of improving the long term results after treatment of meniscal pathology. Thus, the basic clinical principle of contemporary treatment of meniscal tear is to preserve as much functional meniscus tissue as possible while addressing the clinical symptoms caused by meniscal tears.
Fig 1.11: CT Arthrogram of stifle. A: sagittal reconstruction of normal stifle; B: transverse reconstruction of normal stifle; C: sagittal reconstruction of stifle with a medial meniscal tear; D: transverse reconstruction of stifle with a medial meniscal tear (from V.Samii, with permission)
Certain tears are being left untreated and others are being repaired, whereas partial or total excision is advocated only for tears not judged to be suitable for conservative treatment of repair.\textsuperscript{11}

In veterinary orthopaedics, treatment of the meniscus in a patient with CCL rupture remains a controversial topic of discussion. It has been suggested that after CCL surgical repair the medial meniscus may subsequently tear if left intact potentially due to remaining instability.\textsuperscript{45,144} Currently the standard of care is directed toward performing partial or complete meniscectomy if the meniscus is torn, or doing a prophylactic meniscal release or caudal pole hemimeniscectomy if the meniscus is intact.\textsuperscript{145}

First, the clinician should diagnose if there is meniscal pathology, and classify the type of tear. This can be done by MRI, CT arthrogram, ultrasound, arthroscopy or open arthrotomy. If the clinician has a high suspicion of a CCL tear in association with a meniscal tear, arthroscopy or an open arthrotomy is usually performed.

The following techniques for treatment of meniscal injuries will be explained in detail. They include partial, total meniscectomy, caudal pole hemimeniscectomy and, in people, meniscal repair and replacement.

**Arthrotomy**

The medial meniscus may be exposed by arthrotomy through either a cranio-medial stifle approach or a caudo-medial approach to the medial compartment of the stifle (see Fig. 1.12).\textsuperscript{146} Using a cranio-medial approach it is possible to examine the medial and lateral menisci, cranial and caudal cruciate ligaments and articular cartilage of the femoral and tibial condyles (see Fig. 1.12A). Disadvantages of this approach include
extensive soft tissue dissection and difficulty in visualization of the menisci in case of partial CCL rupture. The caudo-medial approach to the stifle is used when there is a stable joint and the medial caudal pole of the meniscus is not visualized easily and if the surgeon does not suspect any other intra-articular pathology (see Fig. 1.12B). Advantages of this technique include less tissue dissection and a better exposure of the caudal pole of the medial meniscus. On the other hand, the rest of the joint cannot be explored.

Fig. 1.12: cranio-medial (A) and caudo-medial (B) approach to the stifle.
Arthroscopy

The meniscus can be also evaluated and treated arthroscopically (see Fig. 1.13). Various types of surgical equipment and techniques are available for arthroscopic evaluation and treatment of meniscal tears. Probing the meniscus is important to assess the damage and to be able to locate the tear which is an important factor in deciding for a meniscectomy. Advantages of arthroscopic diagnosis and treatment of meniscal pathology include less soft tissue trauma to the joint and to the periarticular soft tissue and better magnification of the menisci. The surgeon can visualize each specific region of the menisci, and apply principles of meniscal treatment based on the characteristics of the pathology.

After visualization of both the cranial and caudal portions of the menisci, the surgeon palpates the tibial surface of the meniscus with a probe. Multiple bucket handle tears are more likely to be missed if a thorough palpation is not performed. The surgeon should always attempt to preserve the peripheral rim, by conservatively debriding the damaged part of the meniscus.

Disadvantages of arthroscopy include the steep learning curve and the cost of the instruments. Advantages include better magnification of the menisci, the potential ability to diagnose small tears, and reduced short term morbidity. Arthroscopy caused less short term morbidity in an experimental in vivo study in dogs that underwent CCL repair.
Fig. 1.13: stifle arthroscopy: A: intact medial meniscus; B: meniscal tear.

Medial meniscal release

Currently one of the most popular surgical techniques for management of CCL rupture in dogs is TPLO. It has been recommended that release of the medial meniscus should be routinely performed in conjunction with the TPLO surgery, to prevent development of secondary meniscal injury.
The release procedure is performed by completely transecting the medial meniscus, just caudal to the medial collateral ligament (see Fig. 1.14), or by transecting the caudal menisco-tibial ligament, as illustrated below (see Fig. 1.15).
Fig 1.15: (A) mid body meniscal release; (B) meniscal release at the caudal menisco-tibial ligament.

The purpose is to allow the caudal horn of the medial meniscus to move away from the medial femoral condyle during cranial translation of the tibia and femoro-tibial subluxation (see Fig. 1.16).
Fig 1.16: proposed mechanism for displacement of the caudal pole of the meniscus following medial meniscal release

Medial caudal pole hemi-meniscectomy

Most injuries of the medial meniscus involve the caudal pole, which may present with minimally displaced tears or be folded forward under the femoral condyle. In this position it becomes crushed as a result of the pressure of the femoral condyle. The recommended treatment for caudal pole meniscal injury is caudal pole hemimeniscectomy (see Fig.1.17).
After medial or caudo-medial arthrotomy the peripheral rim of the caudal pole of the medial meniscus is separated from synovial membrane and the meniscus is radially transected at the level of the medial collateral ligament. Then the caudal meniscotibial ligament is transected and the caudal pole is excised.\textsuperscript{138}

![Image of caudal pole hemimeniscectomy](image.jpg)

Fig 1.17: caudal pole hemimeniscectomy.
This procedure is also used as a prophylactic procedure by some surgeons. By removing the caudal pole of a grossly intact meniscus the surgeon prevent late meniscal injury because it eliminates completely the source of injury. However, the load transmission role of the menisci depends upon the integrity of the menisci. Although a meniscus-like structure forms from the synovial membrane after caudal pole hemimeniscectomy in 3 to 6 months, this does not prevent the development of secondary osteoarthritis. 84,134,135,138

Total meniscectomy

Total meniscectomy is defined as removal of the entire meniscus (see Fig.1.18). After separating the medial meniscus from the peripheral synovial membrane the caudal and cranial meniscotibial ligaments are transected and the meniscus is excised.

Advantages of this procedure include removal of tears of the meniscus that are not visualized and opening an access to the vascular capsular attachments, which allows regeneration. The disadvantages are the increase in contact stress, a greater degree of osteoarthritis and a loss of stability. 5, 8, 60, 61, 80, 81, 84, 93-95, 138, 148-150

Total meniscectomy, once the standard treatment for all types of meniscus tears, is now rarely indicated. Only occasionally is a meniscus so severely and extensively damaged that it is necessary to remove the entire meniscus.
Partial menisectomy

As noted through the work of Fairbank, total meniscectomy is not a benign operation. Cox et al found that meniscectomies in canine knees lead to gross and microscopic degenerative changes. They also noted that partial meniscectomies lead to less severe degenerative changes. They believed that there was a direct relationship between the degree of degenerative change and the amount of meniscus removed. Meniscal tears that do not extend to the peripheral rim, may be treated in a more conservative way than a total meniscectomy. A partial meniscectomy is the removal of a
damaged section of the meniscus, while preserving the cranial and caudal meniscotibial ligaments (see Fig 1.19). When performing a partial meniscectomy through an arthrotomy, adequate exposure is facilitated with suction and by using the levering maneuver described previously.

Fig 1.19: partial meniscectomy.
The surgeon grasps the section of the meniscus to be excised and then excises the remaining attachments. Preservation of an intact peripheral rim results in development of less severe osteoarthritis than that associated with complete meniscectomy. Baratz studied the effect of partial and complete meniscectomy on contact area and contact stress in human knees. He found that after partial meniscectomy, contact areas decreased approximately 10%, and peak local contact stresses increased approximately 65%. After total meniscectomy, contact areas decreased approximately 75%, and peak local contact stresses increased approximately 235%. He concluded that partial meniscectomy was valuable to protect the articular cartilage. This is also supported by multiple studies that showed that greater size of meniscal resection was associated with radiographic evidence of more severe osteoarthritis. While performing a partial meniscectomy, the surgeon should preserve the meniscal attachments to the tibia. Partial meniscectomy will preserve some of the load distribution function of the meniscus only when the menisco-tibial ligaments are preserved.

Axial load across the joint is counteracted by circumferential hoop tension which transmits through the circumferentially oriented collagen fibers to the cranial and caudal menisco-tibial ligaments. A radial cut through the meniscus eliminates the hoop tension and disrupts the load transmission function of the meniscus. A radial cut is therefore equivalent to meniscectomy in loading terms.
Meniscal repair and replacement in human patients

The goal in the treatment of meniscal tears in human patients is the preservation of the meniscus when possible. The option to repair the meniscus should always be considered. In the young age group it should be the rule rather than the exception.

Primary repair of the meniscus involves the direct suturing of the meniscus. Although the initial report of meniscal repair was in 1885 by Annandale, it did not become widely performed until almost 100 years later. The meniscal repair is considered in all tears located in the middle third, peripheral third and longitudinal tears including bucket handle tears of the meniscus. Four techniques for meniscal repair are used: open meniscal repair, arthroscopic inside-out repair, arthroscopic outside-in repair, and arthroscopic all-inside repair. Again, the application is a matter of the surgeon's preference and experience. For each of those described techniques, many tools are available on the market including stitching or using anchors or sliding knots. The main advantage of this technique is that the meniscus is left completely in situ. The disadvantages include the technical difficulty and the potential for failure to heal.

Jager reported good long term outcome after meniscal repair in a stable knee in human patients. He suggested that the success of meniscal repair depended upon CCL repair. Venkatachalam reported an overall success rate of 66.1% after meniscal repair in people. Early repair within 3 months of sustaining the tear gave better results (91%) than if carried out later (58%). Suture repair alone yielded better results (78%) than meniscal arrows or a T-fix device (56%). He suggested that the isolated atraumatic
medial meniscal tear might be better treated by meniscectomy.\textsuperscript{156} Shelbourne found no difference in the outcome of bucket handle tears treated by repair or partial meniscectomy.\textsuperscript{157}

Factors that have been shown to favorably affect meniscal repair include acute tears, peripheral tears, a stable knee and the use of exogenous clot or synovial abrasion. Several factors should be considered when selecting a patient for meniscal repair: age, chronicity of the tear, type, location, and associated ligamentous injuries.\textsuperscript{11,125} If the patient does not meet all the ideal characteristics, the indication for meniscal repair remains controversial. However, most authors agree that traumatic tears within the vascular zone should be repaired.

Meniscal repair and replacement in not routinely performed in animal patients. When meniscal repair is not feasible, synthetic or allograft replacements of meniscus are considered to reduce the potential for progressive osteoarthritis associated with meniscectomy. The aims of a meniscal replacement are: 1) to reduce the pain experienced by some patients following meniscus resection; 2) to prevent the degenerative changes of cartilage and the changes in subchondral bone following meniscus resection; 3) to avoid or reduce the risk of osteoarthritis following meniscus resection; 4) to restore optimally the mechanical properties of the knee joint after meniscal resection. The results of meniscus transplantation have been studied in animals. There is no proof from these experiments that replacement of a meniscus can reduce the risk of arthritis, but there are indications.
Basic science and clinical results support the intermediate-term efficacy of allograft meniscus transplantation with substantial pain relief and improved function in symptomatic meniscectomized patients.\textsuperscript{158,159} However, recent studies did not support the hypothesis that meniscal allograft transplantation provided chondroprotection of the femoral condyle.\textsuperscript{160}
CHAPTER 2

IN VITRO EVALUATION OF THE ROLE OF THE MEDIAL MENISCUS IN LOAD DISTRIBUTION IN THE CANINE STIFLE

Introduction

The meniscal fibrocartilages have important functions in load transmission and stability in the femoro-tibial joint. Tearing of the caudal horn of the medial meniscus in conjunction with CCL rupture is a common cause of joint pain. However meniscal injuries may also arise as a late complication to the surgical reconstruction of the CCL deficient stifle by TPLO procedure and other techniques, due to residual joint instability and cranial tibial thrust. The recommended treatment for meniscal injuries found at the time of surgical reconstruction of the CCL deficient stifle is partial or total meniscectomy, depending upon the type of meniscal lesion. However, in cases where the meniscus is found at surgery to be grossly normal, controversy remains over the best way to prevent the development of late meniscal injury. Release of the medial meniscus by radial transection has been recommended as a means of freeing the caudal pole of the medial meniscus so that it may move away from the medial femoral condyle during cranial

49
translation of the tibia, thus preventing development of late meniscal injury. However, medial meniscal release probably disrupts the load transmission role of the menisci because axial loads across the femoro-tibial joint are normally counteracted by hoop tension within the circumferentially oriented collagen fibers.

Complete removal of menisci in humans and experimental animals results in the development of articular cartilage degeneration and osteoarthritis. Furthermore, the severity of osteoarthritis that followed experimental medial, caudal pole hemimeniscectomy in dogs was similar to that arising after complete medial meniscectomy. Disruption of meniscal load transmission results in a decrease in joint contact area which in turn causes the joint surfaces to be subjected to greater loading forces. As a result, supra-physiologic loading of articular cartilage induces an upregulation in synthesis and degradation of cartilage matrix which ultimately leads to mechanical failure of the tissue. Therefore it would be important to determine if medial meniscal release has equivalent deleterious effects on load transmission as meniscectomy in dogs, because routine medial meniscal release may play a role in the development of osteoarthritis in the CCL deficient canine stifle.

We hypothesized that both medial meniscal release and medial, caudal pole hemimeniscectomy would result in disruption of normal load transmission in the medial compartment of the femoro-tibial joint. In order to test our hypothesis we evaluated load transmission in the canine cadaveric stifle joint using a material testing machine and pressure sensitive film. The specific objectives of our study were to determine the effects of medial meniscal release and medial, caudal pole hemimeniscectomy on the magnitude and distribution of pressure on the articular surface of the medial tibial
condyle in the normal canine stifle, and the CCL deficient canine stifle, with and without TPLO.

Material and methods

Materials

Twelve pairs of cadaveric hindlimbs were harvested by disarticulation of the coxo-femoral joint within 2 hours of death from adult male and female dogs that were euthanatized for reasons unrelated to the study. The dogs were of various breeds and were similar in size and body weight (25 to 35 kg). After collection, all soft tissues proximal to the patella were dissected from the limbs, while carefully preserving the rest of the soft tissues distally.

In vitro limb loading

Soft tissues were kept moist during the experiment by spraying the specimens with isotonic saline. A 2.5 mm diameter hole was made in the widest portion of the patella from medial to lateral using a 2.5 mm drill bit. Braided-steel cable (7 x 7 strands) of 1.6 mm diameter was threaded through the hole and secured into a loop using a 9.5 mm-long oval compression sleeve (McMaster-Carr Supply Company; Cleveland, Ohio). An 8 mm diameter Steinman pin was placed through the femur, 2-3 cm distal to the greater trochanter, in a lateral to medial direction to permit subsequent loading of the limb. A 3 cm caudo-medial arthrotomy was performed just caudal to the medial collateral ligament to expose the caudal pole of the medial meniscus to allow for subsequent meniscal treatments and insertion of prescale pressure film. Each limb was mounted in
a servo-hydraulic material test machine (Bionix 858, MTS System Corporation; Eden Prairie, Minnesota) by attaching the proximal Steinman pin to the actuator while the foot was anchored to a custom-made foot-plate (see Fig.2.1). A turnbuckle extending from the femoral neck to the loop of cable in the patella was used to mimic the quadriceps mechanism.

Fig 2.1: in vitro limb loading under material testing machine.
Axial loading of the limbs was performed with the stifle joint at an initial angle of 145°. The test machine was programmed to apply a 200 N axial load in a “ramp up-plateau-ramp down” loading pattern with a 15 s 200 N plateau and a total test duration of 30 s, as previously described.167

Prescale pressure sensitive film

Pressure distributions in joints were measured by use of prescale pressure sensitive films that had a pressure range of 2-10 MPa (SPI Sensor Products Inc, East Hannover, NJ). Prescale films consisted of an A layer and a C layer that had a combined thickness of 0.2 mm (see Fig. 2.2).

Fig 2.2: A: the transfer sheet is A layer and the developer sheet is C layer; B; calibration curve.
The A layer contained microcapsules which ruptured at specific pressures and reacted with a developer contained in the C layer to produce a red stain whose intensity correlated with the magnitude of local pressure (see Fig. 2.2). The color density of the film could therefore be calibrated as a function of the contact pressure (see Fig. 2.2).

The film was cut to match approximately the dimensions of the articular surface of the medial tibial condyle.

Fig.2.3: insertion of the Prescale film through a caudo-medial approach.
Each film had a small tap protruding from the caudo-medial edge that was positioned adjacent to the medial collateral ligament. The films were sealed between two sheets of self adhesive polyethylene (Tegaderm, 3M Health Care, St.Paul, MN) to prevent wetting by synovial fluid. This packet was carefully inserted beneath the medial meniscus through the caudo-medial arthrotomy (see Fig.2.3). After the stifles had been axially loaded, the film was removed. Two to three films were stained for each meniscal treatment. The film with the fewest artifacts was used for the analysis. Films that were damaged during insertion were excluded from the analysis. All procedures were performed by one investigator (KAJ) to reduce variability between subjects.

Experiment 1-Meniscal disruption in normal joints

Six pairs of normal stifles (see Fig.2.4) were axially loaded to determine the pressure distribution in the medial compartment of the femoro-tibial joint to establish control baseline data. Axial loading of each joint was then repeated following medial meniscal release and then medial caudal pole hemimeniscectomy.

Experiment 2-Meniscal disruption and TPLO in cranial cruciate ligament deficient joints

Standard radiographic views (cranio-caudal and medio-lateral) were taken of six pairs of limbs to ensure the stifle joints were free of radiographic evidence of osteoarthritis and for measure of the tibial plateau angle (TPA), using previously described methods (see Fig. 1.3).
Paired limbs were randomly assigned to the standard TPLO group or a sham TPLO group (SHAM) (see Fig. 2.5). The TPLO was performed as previously described to produce a TPA in the range of 5° to 7°. In the SHAM group the standard TPLO procedure was performed without rotating the tibial plateau. Each limb was axially loaded and pressure distributions were recorded in the medial compartment of the femoro-tibial joint with the CCL and the medial meniscus intact, and then again following CCL transection, medial meniscal release, and medial, caudal pole hemimeniscectomy. Two to three films were stained for each meniscal treatment.
Quantification of Prescale Pressure Sensitive Film

The stained films were digitized using a reflective scanner (UMAX 2200, UMAX Australia, Melbourne, Victoria, Australia). After digitalization of the images an oval template was used to define a standard area of interest (Adobe Photoshop 7.0, Adobe Systems Inc, Seattle, WA). The oval template was positioned on the film with the long and short axis parallel to the axis of the film (see Fig. 2.6).
For better repeatability the template was centered on the film and caudally aligned with the tab that defined the position of the medial collateral ligament. The contact stresses were measured as percentages of the total oval area. Parameters of interest for each image were extracted using computerized image analysis techniques with a commercially available programming environment (Interactive Data Language, Research Systems Inc., Boulder, Colorado, USA). This system has the capability of reading area and pressure for all areas of interest as well as providing information about the histogram distribution. From this information we calculated percentages of area corresponding to
pressure ranges of 0 to <4, 4 to <6, 6 to <8, 8 to <10 and ≥10 MPa. Calibration stains of the prescale film were obtained using a material testing machine (Instron 810 Servohydraulic Testing system, Instron, Wycombe, England) by the method of Liggins. This involved the application of twelve different load regimes from 282 to 1131 N. The stains produced were then digitised, resulting in a tabulation of mean red level versus applied pressure. A polynomial of order 5 was used to fit a calibration curve to these data. The calibration curve was then used to convert the red levels in the digitalized contact patterns to pressure units.

Statistical Analysis

Experiment 1-Meniscal disruption in normal joints

Pressure distributions in the three different meniscal treatments were compared with \( \chi^2 \) test for homogeneity. Data from two of 12 stifles were excluded from the analysis due to the presence of artifacts in the films. The remaining 10 stifles were randomly divided into two groups of 5 limbs each. Splitting the data allowed us to compare pressure distributions from different populations. We used pressure distributions samples with an intact meniscus and after medial meniscal release from the first group, and distributions samples of medial meniscal release and medial, caudal pole hemimeniscectomy from the second group for the second comparison. The sum of percentage area of each range of pressure (0 to <4, 4 to <6, 6 to <8, 8 to <10, ≥10 MPa) measured with an intact meniscus in the first group was compared to the sum of percentage area of each range of pressure measured after medial meniscal release in the second group. The sum of percentage area of each range of pressure for medial meniscal
release of the first group was compared to the sum of percent area of each range of pressure for medial, caudal pole hemimenisectommy of the second group.

**Experiment 2-Meniscal disruption and TPLO in cranial cruciate ligament deficient joints**

The pressure range that contributed mostly to the $\sigma^2$ values calculated in experiment 1 was used as an outcome measure to perform the analysis in experiment 2. Data from 4 out of 12 legs were lost due to artifacts in the films. The effect of CCL treatment and meniscal treatment on pressure distribution and their interaction were analyzed using a two-way repeated-measures ANOVA. The factors that were analyzed were TPLO, meniscal treatment and their interaction. Significant differences among groups were evaluated with Bonferroni post-hoc test. Significance for all tests was set at $P < 0.05$.

**Results**

**Experiment 1-Meniscal disruption in normal joints**

Medial meniscal release had a significant effect on the pressure distribution in the medial compartment of the stifle ($P < 0.05$) (see Graph. 2.1).
Graph. 2.1: Mean ± SD percent of area with each pressure range in the intact medial meniscus, medial meniscal release and medial caudal pole hemimeniscectomy groups.

Following medial meniscal release a 2.5 fold increase in percentage of area with peak pressure (>10 MPa) from the control intact stifle was noted (see Fig 2.7, table 2.1).
Fig. 2.7: pressure distribution across the joint with A: intact meniscus, B: medial meniscal release and C: medial caudal pole hemimeniscectomy.
Table 2.1. Distribution of load transmission in normal stifle joints: summary of percent of area with measured ranges of pressure recorded after each treatment (Mean ± SD)

Between groups different letters denote significant difference (P < 0.05)

INTACT, intact meniscus; MMR, medial meniscus release; MCH, medial caudal pole hemi-meniscectomy

In the control intact stifles a third of the area measured in the mid-range of pressure (32% of area with 4 to <6 MPa) whereas in the medial meniscal release stifle a third of the area measured in the peak pressure (35% of area with >10 MPa). The differences between medial meniscal release and medial caudal-pole hemi-meniscectomy for the pressure distribution in the medial compartment were not significant (P > 0.05) (see Table 2.1). A large portion of the $\chi^2$ value was attributable to differences at the 10 MPa range. Following medial meniscal release the peak pressure area lost its central position and shifted caudally, just cranial to the caudal menisco-tibial ligament (see Fig 2.7).
Fig. 2.8: notice the caudal shift of the area of higher pressure in B (medial meniscal release) compared to A (intact meniscus). Pressure sensitive film stained following medial meniscal release illustrates the caudal location of the area of high pressure on the medial tibial plateau.

Experiment 2-Meniscal disruption and TPLO in cranial cruciate ligament deficient joints

The percentage of area with peak pressure values of greater than 10 MPa was used as outcome measure for experiment 2 analysis following the results of experiment 1. We found no significant interaction between TPLO treatment and meniscal treatment, which suggested that we could consider the main effects as true effects of the analyzed treatment (P > 0.05). In the SHAM stifle a significant increase in percent of peak pressure (>10 MPa) was found after transecting the CCL (P < 0.05) (see Graph. 2.2, Table 2.2, Fig. 2.8). Medial meniscal release and medial caudal pole hemimeniscectomy had no further significant effect (P > 0.05). In the TPLO stifle a significant increase in percent of
high pressure was found after medial meniscal release (P < 0.05). Performing medial caudal-pole hemimeniscectomy following medial meniscal release had no further significant effect on percent of high pressure (P > 0.05). A caudal shift of the contact area was noted as in experiment 1 following medial meniscal release and medial caudal pole hemimeniscectomy (see Fig. 2.8).

Graph 2.2: Mean ± SD percent of area with pressure higher than 10 Mpa in the intact medial meniscus and following CCL transection, medial meniscal release and medial caudal pole hemimeniscectomy in the TPLO and SHAM TPLO groups.
Table 2.2. Distribution of load transmission in cranial cruciate ligament deficient stifle joints with and without TPLO: summary of percent of area with peak pressure (>10 MPA) recorded after each treatment (Mean ± SD)

Within TPLO status different letters denote significant difference (P < 0.05)

ICCL+IM, intact cruciate ligament and intact medial meniscus; TCCL+IM, transected cruciate ligament and intact medial meniscus; TCCL+MMR, transected cruciate ligament and medial meniscus release; TCCL+MCH, transected cruciate ligament and medial caudal pole hemi-meniscectomy.

<table>
<thead>
<tr>
<th></th>
<th>ICCL+IM</th>
<th>TCCL + IM</th>
<th>TCCL + MMR</th>
<th>TCCL + MCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPLO</td>
<td>20.68 ± 11.43a</td>
<td>28.08 ± 7.93a</td>
<td>47.48 ± 13b</td>
<td>55.75 ± 12.17b</td>
</tr>
<tr>
<td>SHAM</td>
<td>3.51 ± 2.99a</td>
<td>38.13 ± 11.11b</td>
<td>45 ± 10.9b</td>
<td>52.63 ± 5.45b</td>
</tr>
</tbody>
</table>
Fig. 2.9: Pressure distribution across the joint. A: TPLO stifle with intact CCL and intact meniscus; B, TPLO stifle with transected CCL and intact meniscus; C, TPLO stifle after medial meniscal release; D TPLO stifle following medial caudal pole hemimenisectomy; E, SHAM stifle with intact CCL and intact meniscus; F, SHAM stifle with transected CCL and intact meniscus; G, SHAM stifle after medial meniscal release; H, SHAM stifle after medial caudal pole hemimenisectomy.
Discussion

In our study we found that medial meniscal release, medial caudal pole hemi-meniscectomy and CCL transection in vitro resulted in significant alterations in the load transmission function of the medial meniscus in the canine stifle. After performing a medial meniscal release and similarly a medial, caudal pole hemimeniscectomy in intact and CCL deficient stifle stabilized by TPLO, we observed a focal area of high pressure in the caudal region of the medial tibial condyle. Cranial cruciate ligament transection caused a similar area of high pressure in the CCL deficient stifle that was not stabilized by TPLO.

The role of the menisci as load bearing elements have been already studied in depth in human and animals models. Several studies have shown that meniscectomy causes an immediate, acute increase in stifle contact peak pressure and that these changes in stress distribution cause remodeling of bone and soft tissue. Ahmed and Burke reported that removal of the medial meniscus caused a reduction in the compartment area by 50-70% and a marked increase in peak pressure in the human knee. Krause showed that canine menisci transmit 65% of the weight bearing and that a two-fold increase in compression deformation of cartilage and subchondral bone occurred after meniscectomy. Shrive reported that radial transection of the porcine and human meniscus was equivalent to meniscectomy in terms of load-bearing, suggesting the loss of hoop tension was responsible for high and non-uniform pressure distribution. In our experiment we found that the medial meniscus is an important load bearing element in the normal and CCL deficient canine stifle stabilized by TPLO. Medial meniscal release and medial, caudal pole hemimeniscectomy eliminated the load transmission function of
the meniscus and produced a two-fold increase in peak pressure area and a non-uniform pressure distribution. These results are similar to what previous authors reported after total meniscectomy in canine and human models. As Shrive suggested, transection of the circumferential fibers of the meniscus disrupts the hoop tension which is responsible for the load bearing function.\textsuperscript{72}

In a previous study of load transmission in canine stifles, it was found that CCL transection caused a caudal shift of the stifle contact areas, without any change in pressure magnitude.\textsuperscript{171} In our study we likewise found a caudal shift of the contact area following CCL transection but we noted a significant increase in peak pressure. The different results of the two studies may be related to the different model, film sensitivity or specimen preparation. The caudal shift of the area of high peak pressure probably occurred during cranial tibial translation. During weight bearing on an unstable stifle, the medial femoral condyle shifts caudally and loses its normal central position in the crescent shape meniscus.\textsuperscript{39} This condylar translation may disrupt the hoop tension by applying a high pressure in a peripheral area of the meniscus and potentially increasing the risk of injury of the caudal pole of the meniscus. In our study we also found that the magnitude of peak pressure diminished in the stifle treated by TPLO, suggesting that the detrimental effect of CCL transection on load transmission was eliminated by neutralizing the cranial tibial thrust with TPLO.\textsuperscript{166} Performing a tibial plateau leveling osteotomy in the presence of an intact meniscus may maintain the load transmission function of the medial meniscus in a CCL deficient stifle. The results of the pressure distributions in TPLO stifles suggested some interesting points of discussion. Despite a homogenous distribution, the magnitude of the pressure measured in the normal stifle
with TPLO was higher than in the normal stifle without any treatment. This would suggest that TPLO may change the normal stifle biomechanics and may increase the forces acting on the tibial plateau without changing its distribution.

The link between meniscal damage or meniscectomy and osteoarthritis is not well understood.\textsuperscript{86,102-106} It has been proposed that compression of the cartilage at physiological strains serves as a signal to modulate chondrocyte responses, while prolonged compression at higher strains may be responsible for tissue and cell damage.\textsuperscript{86} Radin et al reported that failure of a damaged or resected meniscus to attenuate peak dynamic force may predispose to subchondral bone stiffening and consequently osteoarthritis.\textsuperscript{107,108} Clements reported that repetitive compressive loading with peak stress ranging between 3.5 and 14 MPa caused an immediate dose-related increase in collagen denaturation in bovine articular cartilage.\textsuperscript{83} There is also a body of clinical literature that suggest that surgical removal of the medial meniscus constitutes a risk factor for the later appearance of joint cartilage changes.\textsuperscript{8,9,109} In our study we measured a focal peak pressure on the cartilage of the caudal medial tibial plateau higher than 10 MPa following medial meniscal release and medial, caudal pole hemimeniscectomy. This observation suggests that the caudal region of the medial compartment of stifle could be at higher risk of cartilage damage after medial meniscal release and medial, caudal pole hemimeniscectomy. This is consistent with a recent experimental and clinical studies which found early cartilage degeneration of the medial femoral condyle and medial caudal tibial plateau following medial meniscal release and medial, caudal pole hemimeniscectomy.\textsuperscript{138}
In our model, load transmission was evaluated by measurement of magnitude and distribution of pressure using pressure sensitive films. Pressure sensitive film has several limitations, notably the range between threshold and saturation and the sensitivity of the film to loading rate and environmental conditions. The peak pressures of the CCL deficient joints and that of the stifle after medial meniscal release or medial, caudal pole hemimenesectomy were beyond the 10 MPa thresholds. In our study we considered pressures higher than 10 MPa as supraphysiologic as suggested by previous studies (Clements, 2001 #182). The results from pressure sensitive film also are affected by shear stresses, the time between testing and analysis, and environmental conditions. These effects were certainly present in this study but were not considered to affect the results significantly, mainly because the differences between paired limbs were the most important variables. The method of sampling pressure, defined as percent of area with the range of pressure, was chosen because it was judged to depend less on artifacts than did other reported methods (Bylski-Austrow, 1993 #137). In our study we did not measure the contact area or its shift. Previous studies suggested that pressure is a more sensitive indicator of meniscal function. We chose to describe qualitatively both width and shift of contact area because we could not find a method free of potential bias. The loading rate was based on previous work which showed that the film results were more consistent when the time to reach peak load exceeded 15 s.

In conclusion our results show that both medial meniscal release and similarly medial, caudal pole hemimenesectomy significantly affect the load transmission function of the meniscus and consequently the cartilage pressure. Our study also found that TPLO neutralizes the negative effect of CCL transection on load transmission. The implication
of these data for clinical use is that an intact meniscus should be ideally preserved in the CCL deficient stifle stabilized by TPLO. Maintaining the load bearing function of the medial meniscus may protect the articular cartilage from supra-physiologic pressure and its potential detrimental effects on cartilage metabolism. Further studies are needed to determine if medial meniscal release is necessary in CCL deficient stifles treated by TPLO.
CHAPTER 3

IN VITRO EVALUATION OF THE ROLE OF THE MEDIAL MENISCUS IN THE JOINT STABILITY IN THE CANINE STIFLE

Introduction

The combination of cranial cruciate ligament (CCL) rupture and medial meniscal tear is a common clinical problem in dogs. The medial meniscus may be torn acutely at the time of CCL rupture or more likely, become damaged over time as a result of chronic instability and cranial tibial translation. Partial or total meniscectomy have been recommended if the meniscus is found to be partially or completely torn. However, controversy still exists regarding the best way of treating dogs with a ruptured CCL and a grossly intact medial meniscus. Multiple clinical and cadaveric studies have established the role of the medial meniscus as a secondary stabilizer of the anterior cruciate ligament (equivalent to CCL in dogs) deficient human knee. The posterior pole of the medial meniscus may act as a wedge, limiting the degree of posterior displacement of the medial femoral condyle in the anterior cruciate ligament deficient human knee. This role as a secondary restraint in the anterior cruciate ligament deficient knee may expose the medial meniscus to increased shear forces during weight bearing on the limb and risk of injury.
Slocum recommended that medial meniscal release be performed to eliminate the wedge effect, allowing caudal retraction of the caudal pole of the meniscus away from the femoral condyle, and thereby preventing late meniscal injury in the CCL deficient canine stifle following neutralization of cranial tibial thrust by tibial plateau leveling osteotomy (TPLO). Medial meniscal release can be performed either by complete radial transection of the meniscus just caudal to the medial collateral ligament or by transection of the caudal menisco-tibial ligament. Prophylactic medial, caudal pole hemimeniscectomy has been proposed as an alternative to medial meniscal release, based on the assumption that the two procedures have similar effects on the stifle joint. After radial transection of the meniscus, circumferential tension cannot be developed and consequently load transmission by the meniscus is impaired. This loss of functional load transmission has detrimental effects on the articular cartilage and causes cartilage degeneration. Both medial meniscal release and medial, caudal pole hemimeniscectomy have been shown to result in the development of osteoarthritis. However, to our knowledge, the effects of medial meniscal release and medial caudal pole hemimeniscectomy on the stability of the CCL deficient stifle with TPLO have not been investigated previously.

We hypothesized that the medial meniscus acts as a secondary restraint against tibial translation in the CCL deficient canine stifle and that both medial meniscal release and medial, caudal pole hemimeniscectomy would allow further subluxation and displacement of the caudal pole of the medial meniscus, irrespective of the tibial plateau angle. In order to test our hypothesis, we evaluated canine stifle joint stability and motion of the caudal pole of the medial meniscus using an in vitro limb loading press and
radiographic imaging of radiopaque markers placed on the joint and the medial meniscus. The specific objectives of our study were to determine the effects of medial meniscal release and medial, caudal pole hemimeniscectomy on cranial tibial translation and on motion of the caudal pole of the medial meniscus in the CCL deficient canine stifle, with and without TPLO.

**Material and methods**

**Materials**

Paired cadaveric hind limbs were harvested within 2 hours of death from adult male and female dogs that were euthanatized for reasons unrelated to the study. The dogs were of various breeds and were similar in size and body weight (25 to 35 kg). Standard radiographic views (cranio-caudal and medio-lateral) were taken of each limb to ensure that the stifle joints were free of radiographic evidence of osteoarthritis and for measure of the tibial plateau angle, using previously described methods. Only joints with a tibial plateau angle in the range of 24° to 30° were used for the study. All soft tissues proximal to the patella were dissected from the limbs, while carefully preserving the rest of the soft tissues. The specimens were wrapped in saline-soaked towels and stored at -70° C until testing, at which time they were thawed at room temperature.

**In Vitro Limb Loading**

Soft tissues were kept moist during the experiment by spraying tissues with isotonic saline. The femur was osteotomized just distal to the greater trochanter using an oscillating sagittal saw. A 2.5 mm diameter hole was drilled transversely through the
widest portion of the patella. Braided-steel cable (7 x 7 strands, McMaster-Carr Supply Company, Cleveland, Ohio) of 1.6 mm diameter was threaded through the hole in the patella and secured into a loop using a 9.5 mm-long oval compression sleeve (McMaster-Carr Supply Company, Cleveland, Ohio). To permit the subsequent evaluation of femorotibial subluxation in the sagittal plane, radiopaque fiducial markers were placed in the distal femur, and in the proximal tibia, just caudal to the origin and insertion of the medial collateral ligament respectively (see Fig. 3.1).

A 4 cm cranio-medial arthrotomy was performed to expose the CCL. A 3 cm caudo-medial arthrotomy situated just caudal to the medial collateral ligament, was also performed to expose the caudal pole of the medial meniscus. These arthrotomies were performed before any data were collected so that any effect on joint stability could be separated from the effects of CCL transection, medial meniscal release and medial, caudal pole hemimeniscectomy.

The caudal pole of the medial meniscus was exposed through the caudo-medial stifle arthrotomy and marked with a radio-opaque stainless steel hemostatic clip (2 mm Large Ligaclip Extra, Ethicon Endo-Surgery, Inc, Cinicinnati, Ohio) to allow the position of this structure relative to the tibia and the femur to be studied.
Fig 3.1: A: TW is the tibial width. X₀ and Y₀ are the distances between femoral and tibia markers before treatment. Then, after each treatment a vector TTᵥ is calculated as shown in figure B. Fo and To are respectively the pre-treatment distances of the caudal pole of the meniscus from the femoral and tibial markers.

A two-pin type I external fixator was applied to the tibia with the proximal pin approximately 4 cm distal to the fibular head and the distal pin 3 cm proximal to the malleoli. The femoral diaphysis was fixed into a 12 cm long aluminum tube of 3.3 cm
diameter using four to six 3.5 mm-cortical screws (Synthes USA, Monument, CO).
The angle of the stifle was measured at the intersection between a line parallel to the aluminum tube and the connecting rod of the external fixator (see Fig.3.2).

Fig. 3.2: in vitro limb loading in the custom made limb press.
Each limb was mounted in a custom made loading frame with the femoral longitudinal axis at 20° to a vertical reference plumb-line. A cable and a turnbuckle extending from the aluminum tube to the patella were used to mimic the quadriceps mechanism (see Fig. 3.2). Before loading each specimen the turnbuckle was adjusted to fix the stifle at an angle of 135° while a load of approximately 20% of body weight was being applied. After transection of the CCL and before starting the meniscal treatments the stifle angle was readjusted to 105 degrees ± 5 degree. Medio-lateral radiographs of the limb were taken before and after each intervention (CCL transection, medial meniscal release, medial, caudal pole hemimeniscectomy and TPLO) using high speed films (X-Sight L/RA Film, Kodak, Rochester, NY) in an 18 x 43 cm cassette (Lanex Extremity Cassette, Kodak, Rochester, NY) with corresponding intensifying screens (Lanex Fine Screens, Kodak, Rochester, NY) and a portable radiographic machine (HF-100, MinXRay Unit, Northbrook, IL) using a focal point-to-film distance of 49 cm and standardized exposure parameters (54 KvP, 10 MAS). All exposures included the proximal aluminum tube and the entire tibia, with the radiographic beam perpendicular to the vertical plumb line and centered on the femoro-tibial joint. Radiographs and surgical procedures were performed by a single investigator (AP) to reduce variability.

Our isolated canine limb model simulated weight bearing on the stifle joint by the application of a vertical load while the joints were fixed at physiologic weight bearing angles. We used a flexibility approach to study the relative importance of the meniscus as a secondary restraint after different surgical interventions. This approach involved
measuring a displacement produced by a load before and after transection of a soft tissue structure. The relative difference in displacement was then used to establish the importance of the structure in femoro-tibial joint stability.\textsuperscript{166, 174, 175}

**Experiment 1 – Effect of medial meniscal release on tibial translation in normal and cruciate deficient stifles**

Sixteen pairs of limbs were used for the study. Within pairs, joints were randomly assigned for testing with an intact CCL or a transected CCL to determine the effects of medial meniscal release and medial, caudal pole hemimeniscectomy on cranial tibial translation (see Fig.3.3). In the transected CCL group, the initial radiograph of the loaded limb was taken, then the limb was unloaded by 10 % of body weight and the CCL was sharply transected with a number 11 scalpel blade. Another radiograph of the limb was taken after reapplication of the load. Without unloading the limb or modifying the joint angle, medial meniscal release was performed by completely transecting the medial meniscus just caudal to the medial collateral ligament and another radiograph was taken.
After partially unloading the limb, a medial, caudal pole hemimeniscectomy was performed and the final radiograph was taken of the loaded limb. In the intact CCL group every step except CCL transection was performed as described for transected CCL group. In a subset of ten pairs of limbs selected at random, the medio-lateral radiographic images that were obtained before and after medial meniscal release were also used to evaluate caudal displacement of the caudal pole of the medial meniscus relative to the tibia and the femur.
After collection of the data each specimen was dissected to confirm that CCL transection, medial meniscal release and medial, caudal pole hemimeniscectomy had been correctly performed.

Experiment 2 - Effect of medial meniscal release on tibial translation in the cruciate deficient stifle after tibial plateau leveling osteotomy

Fifteen pairs of limbs were used for the study. In addition to the standard preparation of limbs described previously, the CCL in all joints was transected. Within pairs the joints were randomly assigned to the TPLO or the sham operated TPLO (SHAM) groups (see Fig. 3.4), and studied to determine the effects of medial meniscal release and medial, caudal pole hemimeniscectomy on cranial tibial translation. The standard TPLO procedure was performed as previously described using a 24 mm TPLO saw blade. The proximal metaphyseal segment of the tibia was rotated so as to produce a tibial plateau angle within the range of 5° to 7°, and fixed with a six-hole 3.5-mm plate (Slocum Enterprise, Eugene, OR) and six 3.5 mm-cortical screws (Synthes USA, Monument, CO). The same surgical procedure was performed in the SHAM stifle without altering the tibia plateau angle. In both the TPLO and SHAM groups, limbs were loaded, radiographed and then tested for the effect of medial meniscal release and medial, caudal pole hemimeniscectomy as described for experiment 1.
In a subset of ten pairs of limbs selected at random, the medio-lateral radiographic images that had been obtained before and after medial meniscal release were also used to evaluate caudal displacement of the caudal pole of the medial meniscus relative to the tibia and the femur.
Radiographic measurement of cranial tibial translation and displacement of the caudal pole of the medial meniscus

All radiographs were converted to digital images at 400x400 dpi and an 8-bit depth of grayscale by means of a high resolution flatbed scanner (Lumisyn Inc, Sunnyvale, CA) and an image analysis software (Lumiscan, Davis, CA). The digital images were exported as uncompressed tagged-image file format files and analyzed using commercial software (Adobe Photoshop 7.0, Adobe Systems Inc, Seattle, WA). Change in magnification between radiographs was controlled by ensuring that the variation between radiographs of the distance AB of the same specimen was not greater than 0.2 mm (see Graph. 3.1). Measurement of tibial translation was accomplished by measuring the initial horizontal($X_0$) and vertical distance ($Y_0$) of the tibial marker from the femoral markers to establish the control position (see Fig. 3.1). Following each meniscal treatment, marker distance was remeasured, and horizontal ($X_\alpha - X_0 = x$) and vertical displacement ($Y_\alpha - Y_0 = y$) relative to the control position was calculated (see Fig. 3.1). A linear displacement vector of tibial translation ($TT_v$) was calculated using the horizontal and vertical displacement data by the following formulae ($TT_v = \sqrt{x^2 + y^2}$) (see Fig. 3.1). To control for variability in bone size this vector was normalized to the width of the tibia by dividing $TT_v$ by tibial width and multiplying by 100 (normalized $TT_v$) (see Fig. 3.1). Tibial width was measured at the most cranial point of the tibial tuberosity perpendicular to the long axis of the tibia using mediolateral radiographs of the normal tibia (see Fig. 3.1).

Quantification of caudal displacement of the caudal pole of the medial meniscus was accomplished by measuring the initial horizontal distance ($T_0$) of the meniscal
marker from the tibial marker and the initial horizontal distance \((F_0)\) of the meniscal marker from the femoral marker to establish the control position (see Graph. 3.1).

Following each meniscal treatment, marker distances from the tibia and the femur were remeasured and respective horizontal displacements relative to the control position were calculated (tibia: \(T_{x} - T_0 = T\); femur: \(F_{x} - F_0 = F\)) (see Graph. 3.1).

**Statistical Analysis**

In experiments 1 and 2 we designated a neutral tibial displacement before starting the meniscal treatment, as previously described. All subsequent changes in position of the tibia were measured as displacement from the neutral position. By accepting the position of the loaded stifle before meniscal treatments as neutral for both groups, the main effects as well as the interaction could be analyzed with a two-way ANOVA. The magnitude of displacement due to CCL transection was not considered in the analysis because it preceded the neutral position.

For the study of effects of CCL transection and TPLO, the tibial translation data were analyzed in a repeated measure two-way ANOVA using PROC MIXED in SAS 9.1 (SAS Institute, Cary, NC). In Experiment 1, the main effects for the factors CCL and meniscus status (medial meniscal release and medial, caudal pole hemimeniscectomy) and their interaction were explored. In Experiment 2, main effects for the factors TPLO and meniscus status and their interaction were explored. Significant main or interaction effects were considered to be present at a \(p\)-value < 0.05. Significant differences among groups were evaluated with Tukey’s post hoc test for all pairwise comparisons of means.
The displacement of the caudal pole of the medial meniscus relative to tibia and femur in intact and transected CCL stifles and in TPLO and SHAM stifle were compared using a paired t test (GraphPad Prism 4, GraphPad Software, Inc., San Diego, CA). Significant difference was considered to be present at a p-value < 0.05.

Results

Experiment 1 – Effect of medial meniscal release on tibial translation in normal and cruciate deficient stifles

Transection of the CCL resulted in a grossly evident tibial translation as well as a change in stifle joint angle of greater than 2°. Therefore the displacement data corresponding to CCL transection were excluded from the statistical analysis and reported as descriptive data, due to this variation in stifle angle (see Graph 3.1, Table 3.1, Fig. 3.5). Analysis of the displacement data found that there was a significant (non-zero) tibial displacement for all combinations of CCL and meniscus status. Comparison of means for the interaction terms found that there were no significant differences in tibial translation between medial meniscal release and medial caudal pole hemimeniscectomy in either the CCL deficient or the intact CCL stifles. However, medial meniscal release (P < 0.05) and medial caudal pole hemimeniscectomy (P < 0.05) effects on tibial translation were significantly greater in CCL deficient stifles than in intact CCL stifles. The displacement effects are summarized in Graph 3.1, Table 3.1. Medial meniscal release caused significantly greater caudal displacement of the caudal pole of the medial meniscus relative to the tibia and to the femur in the transected CCL stifle than in the intact CCL stifle (P < 0.05) (see Graph 3.2 and Table 3.2).
Graph. 3.1: Effect of medial meniscal release and medial caudal pole hemimenisectomy on tibial translation in stifles with intact or a transected CCL.
Table 3.1: Tibial Translation in Normal and Cranial Cruciate Deficient Canine Stifles (mean ± SD). The different letters denote significant difference between groups (P < 0.05). Intact, intact cruciate ligament; transected CCL, transected cruciate ligament; NA, not available.

<table>
<thead>
<tr>
<th>CCL status</th>
<th>Transected CCL</th>
<th>Medial Meniscal release</th>
<th>Medial Caudal pole hemimenisectomy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intact</td>
<td>NA</td>
<td>1.9 ± 1.02^a</td>
<td>2.04 ± 1^a</td>
</tr>
<tr>
<td>Transected</td>
<td>28.2 ± 9.1</td>
<td>6.08 ± 1.42^b</td>
<td>6.13 ± 1.63^b</td>
</tr>
</tbody>
</table>
Fig. 3.5: radiographs taken before treatment (A and D) and after medial meniscal release (B and E), and medial caudal pole hemimeniscectomy (C and F) in the intact and deficient CCL stifle.
Graph 3.2: Displacement of the Caudal Pole of the Medial Meniscus after Medial Meniscal Release in Normal and Cruciate Deficient Stifles (mean ± SD).

<table>
<thead>
<tr>
<th>stifle status</th>
<th>From tibia</th>
<th>From femur</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intact</td>
<td>0.8±0.4 mm a</td>
<td>0.8±0.6 mm a</td>
</tr>
<tr>
<td>Transected</td>
<td>1.9±0.8 mm b</td>
<td>1.6±0.8 mm b</td>
</tr>
</tbody>
</table>

Table 3.2. Displacement of the Caudal Pole of the Medial Meniscus after Medial Meniscal Release in Normal and Cruciate Deficient Stifles (mean ± SD)

The different letters denote significant difference between groups (P < 0.05)

Intact: intact cruciate ligament; Transected: CCL deficient stifle; from tibia: displacement of the caudal pole of the medial meniscus relative to tibia; from femur: displacement of the caudal pole of the medial meniscus relative to femur.
Experiment 2 - Effect of medial meniscal release on tibial translation in the cruciate deficient stifle after tibial plateau leveling osteotomy

We found a significant interaction between CCL treatment with TPLO and meniscal treatments. The effect of medial meniscal release on tibial translation was significantly greater in SHAM stifles than in TPLO stifles (see Graph.3.3, Table 3.3; Fig. 3.6). We also found that medial, caudal pole hemimeniscectomy did not cause any additional displacement after medial meniscal release, regardless of TPLO status. The remaining main effects of each factor are reported in Graph 3.3 and table 3.3. Medial meniscal release caused significantly greater caudal displacement of the caudal pole of the medial meniscus relative to the tibia and to the femur in the SHAM stifle than in the TPLO stifle (P < 0.05) (see Table 3.4).
Graph. 3.3: Effect of medial meniscal release and medial caudal pole hemimeniscectomy on tibial translation in stifles with TPLO or SHAM (A).
Table 3.3: Tibial Translation in Normal and Cranial Cruciate Deficient Canine Stifles (mean ± SD). The different letters denote significant difference between groups (P < 0.05). TPLO, tibial plateau leveling osteotomy; SHAM, sham tibial plateau leveling osteotomy.
Fig 3.6: Radiographs taken before treatment (A and D) and after medial meniscal release (B and E), and medial caudal pole hemimeniscectomy (C and F) in the CCL deficient stifles treated by TPLO or untreated (SHAM).
Table 3.4. Displacement of the Caudal Pole of the Medial Meniscus after Medial Meniscal Release in Cruciate Deficient Stifles with and without TPLO (mean ± SD).

The different letters denote significant difference between groups (P < 0.05)

TPLO: CCL deficient stifle stabilized by TPLO; SHAM: CCL deficient stifle not stabilized by TPLO; from tibia: displacement of the caudal pole of the medial meniscus

<table>
<thead>
<tr>
<th>stifle status</th>
<th>From tibia</th>
<th>From femur</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPLO</td>
<td>0.5±0.4 mm</td>
<td>0.6±0.6 mm</td>
</tr>
<tr>
<td>SHAM</td>
<td>2.4±1.1 mm</td>
<td>1.8±0.9 mm</td>
</tr>
</tbody>
</table>
Discussion

In our study we found that the medial meniscus plays an important role as a secondary stabilizer in the canine stifle, similar to what is described in humans. In the CCL deficient canine stifle the medial meniscus becomes the primary restraint against the cranial tibial thrust as the caudal pole act as a wedge between femoral and tibial condyles. We found that the stabilizing effect of the caudal pole of the medial meniscus in the CCL deficient stifle seemed to be less important after TPLO had been performed. This would suggest that TPLO may unload and protect the caudal pole of the meniscus from injury due to femoro-tibial subluxation.

The role of the menisci as stabilizing elements has been already studied in depth in human and animals. In 1982 Levy and coworkers evaluated the effect of meniscectomy on knee motion before and after transection of the anterior cruciate ligament in cadaveric human knees. Levy found that as anteriorly directed force was applied to the tibiae of anterior cruciate ligament deficient knees, the medial meniscus acted as a wedge between the femur and the advancing tibia, restraining the tibia from further displacement. From this study it was concluded that anterior tibial translation was greater in knees that lacked both a medial meniscus and an anterior cruciate ligament than in knees with an isolated anterior cruciate ligament rupture. There are some major anatomical differences between dogs and humans in the femoro-tibial joint. During stance phase, the angle of the canine stifle is of 135° and of the human knee is about 180°. In both species the tibial plateau is not perpendicular to the tibial shaft axis but has a caudal slope. In humans this slope is 5° to 10° and in dogs is about 23°. A steeper tibial slope is responsible for a cranially directed force acting on the tibia during
weight bearing, called cranial tibial thrust, causing cranial tibial translation in a CCL
deficient stifle. In our study the cranial tibial thrust acted on the tibia as the
anteriorly directed force that Levy applied to the human tibia. The limitation of using
cranial tibial thrust in a flexibility model is its variability between subjects. We
limited this variability by controlling for the tibial plateau angle, body weight and axial
load. Despite these species differences, our findings supported Levy’s hypothesis.
We found that joint stability of the intact canine stifle was only minimally affected by
release or removal of the caudal pole of the medial meniscus, suggesting that the medial
meniscus is a secondary restraint in presence of an intact CCL. We also found
that the effect of meniscal release on joint stability was not different from caudal pole
hemimeniscectomy, suggesting that the former has no advantages over the second for
contributing to stifle stability. As Levy described, we observed a wedge effect of the
caudal pole of the medial meniscus preventing the tibia from further subluxation in the
CCL deficient stifle. The posterior horn of the medial meniscus might encounter shear,
potentially explaining the high rate of secondary medial meniscal tears in patients with
CCL deficiency. Recently it has been also suggested that cyclic tensile strain may
increase the production of nitric oxide and prostaglandin E(2) in a manner that depended
on strain magnitude. This suggests that both biomechanical and inflammatory factors
could contribute to the progression of joint disease as a consequence of altered loading of
the meniscus.

Medial meniscal release has been recommended to eliminate the wedge effect of
the meniscus in the CCL deficient stifle treated by TPLO. Meniscal release may
eliminate the wedge effect by freeing the caudal pole from its attachments to the tibia, as
suggested by the significant displacement of the caudal pole after meniscal release in the CCL deficient stifle. The effects of meniscal release on displacement of the caudal pole of the meniscus and tibial translation seemed less significant following TPLO, implying that the wedge effect is significantly smaller when cranial tibial thrust is neutralized by TPLO. This would also suggest that the risk of late meniscal injury would be less in a CCL deficient stifle stabilized by TPLO than in an untreated CCL deficient stifle. Our results provide a rationale for stabilizing a CCL deficient stifle with an intact medial meniscus to reduce the risk of subsequent meniscal injury. In addition TPLO may protect the caudal pole from injury and meniscal release may not be needed. However, a major limitation of these conclusions is that this was an in vitro study with the joint loaded at one fixed angle. This model did not account for events during flexion and extension. Treatment of a patient with a torn meniscus remains a recurrent topic in human orthopaedic literature. Currently, the standard care is directed toward surgical repair or conservative partial meniscectomy. In contrast, in veterinary orthopaedics, prophylactic procedures such as medial meniscal release or caudal pole hemimeniscectomy are routinely performed on grossly normal menisci. We previously found that these procedures are detrimental on load transmission function. The present study showed that meniscal release and caudal pole hemimeniscectomy also eliminate the stability function of the meniscus. Stifle joint congruency, which is a function of the geometry of the articulating surfaces, is a major factor contributing to the stability of a diarthrodial joint. The menisci deepen the tibial surface to fit the femoral condyles and fill the void between the two bones. By preserving the medial meniscus and neutralizing the
tibial thrust it may be possible to preserve stability and uniform distribution of load across the joint through the wide range of motion of the stifle joint.

This study demonstrated the utility of this flexibility model in exploring the functional interaction between CCL and the medial meniscus. It also provides the groundwork for further investigations on alternative meniscal treatments that may preserve the stability function and CCL reconstruction techniques that best restore the biomechanics of the stifle. One of the limitations of our study is that varus-valgus and internal-external instability were not evaluated. Previous investigations have shown an increase in rotational laxity after medial and lateral meniscectomy in canine and human experimental models. Additional studies in canine models are needed to evaluate contribution of the medial meniscus to rotational stifle stability after TPLO.

In conclusion our results suggest that TPLO unload the medial meniscus and decrease the risk of impingement of the caudal pole between the femur and the tibia during weight bearing. Further clinical studies should be done to confirm if medial meniscal release is necessary to prevent late meniscal injury in the CCL deficient stifle.
CONCLUSION

In human orthopaedics attitudes toward the treatment of meniscal tears have changed dramatically in the last 50 years. As evidence has accumulated from both animal and clinical studies of the development of degenerative changes following meniscectomy, surgeons have become increasingly aggressive in their efforts to conserve as much meniscal tissue as possible. In contrast, a more liberal approach to meniscal treatment is still common among veterinary orthopedic surgeons. Partial and total meniscectomy are recommended if the meniscus is torn. In the presence of a grossly normal meniscus, it has been recommended to perform a meniscal release in an attempt to prevent late injury. The efficacy of this technique and the long term effect on the articular cartilage are unknown, and the decision of releasing an intact medial meniscus remains controversial. Some surgeons argue that meniscal release eliminates the functions of the meniscus, while others think that the risk of late meniscal injury is too high.

The preemptive meniscal release or hemimenisectomy would be justified if the risk of late injury were unacceptably high, if the canine meniscus were functionless structure, or if the meniscal functions were conserved after meniscal release. The reported incidence of meniscal tears occurring after CCL stabilization that required a second surgery is about 14 percent. The incidence of meniscal injury in patients treated with
TPLO and meniscal release is about 2 percent. The results of these studies are difficult to compare because of the presence of confounding factors including differences in weight, breed, type of CCL tear, CCL repair technique, meniscal evaluation technique, surgeon’s experience, long term follow-up period. Obesity, complete CCL tear, chronicity of the CCL rupture, severe stifle instability are risk factors for meniscal tears and they may have skewed the results of these studies. Meniscal release has been proposed as a “benign alternative” to hemi-meniscectomy or total meniscectomy. The development of arthritis after hemi- or total meniscectomy is well documented. Recent retrospective studies have evaluated the progression of osteoarthritis following TPLO and meniscal release, but the results are controversial and the power of the studies is low. Our results showed that medial meniscal release has detrimental effects on load transmission and joint stability similarly to medial caudal pole hemi-meniscectomy. This would suggest that medial meniscal release might predispose to osteoarthritis as much as medial caudal pole hemimeniscectomy. However this hypothesis should be confirmed with an in vivo study.

Based on our results we cannot make any clinical recommendation. In vitro studies have the lowest value in literature using evidence based medicine criteria. However, these results can be used to design future clinical prospective studies that may define what approach should be done with meniscal treatment.

Limitations of our study include the inability to evaluate chronic CCL deficiency, which may cause periarticular fibrosis and osteoarthritis in the clinical patient and consequently decrease the meniscal wedge effect and change the pressure distribution. This would be more clinically relevant, but the variability between subjects in interval
between trauma and experiment, and in magnitude of fibrosis and osteoarthritis would be
difficult to control. We also used an axial load that may be lower than in an in vivo
situation. The meniscus may be subjected to higher forces during exercise. Another
limitation that we encountered in the load transmission study was the presence of artifacts
in the pressure sensitive films. Previous reports have described advantages and
disadvantages of this technique.\textsuperscript{168} Limitation of the pressure sensitive films include the
limited range between threshold and saturation, shear stresses, the time between testing
and analysis and the method of sampling pressure.\textsuperscript{97,168} These effects certainly were
present in the study but were not considered to affect the results significantly, mainly
because the differences in pressure between paired limbs were the most important
variables. We did not measure the contact area between femur and tibia. Because
pressure is defined as force divided by contact area, changes in compartment area clearly
are a mechanism of change in pressure. Contact area is more sensitive to the threshold
limit and to the joint motion. The best way to evaluate contact area would have been to
use a casting method but we believe that defining the pressure distribution was enough to
discuss our hypothesis.

Medial meniscal release was initially recommended together with TPLO to
prevent the wedging of the caudal pole of the medial meniscus due to stifle instability.
However it has been demonstrated that TPLO eliminates the cranial tibial thrust, which is
an important component of the instability found in the CCL deficient stifle.\textsuperscript{39,45,166,186}
Based on these published studies one may conclude that meniscal release is not needed
following stabilization of a CCL deficient stifle with TPLO, or in presence of a stable
partial CCL rupture. However, early unpublished data suggested that there was a high
incidence of meniscal tears following TPLO. Our study showed that TPLO may protect
the caudal pole of the medial meniscus from the cranial tibial thrust, but does not
demonstrate if this protective effect is enough to prevent late injury to the meniscus.
Rotational instability, or poor muscle tone may prevent a complete neutralization of the
tibial thrust in clinical patients. Thus, we cannot conclude that we can safely stop doing
meniscal release in all clinical patients.

The future developments of these studies are most likely clinical research. Despite
being challenging, time and money consuming, a well designed clinical study may
answer important questions concerning the need for meniscal release, the selection of the
candidates for this procedure and its long term effects on articular cartilage.
BIBLIOGRAPHY


104. Berthiaume MJ, Raynauld JP, Martel-Pelletier J, et al. Meniscal tear and extrusion are strongly associated with progression of symptomatic knee osteoarthritis as


