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Long-Term Outcome in Dogs After Surgical Repair of Cranial Cruciate Ligament Disease

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LONG-TERM OUTCOME IN DOGS AFTER SURGICAL REPAIR OF CRANIAL CRUCIATE LIGAMENT DISEASE

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ACADEMIC DISSERTATION

To be presented, with the permission of the Faculty of Veterinary Medicine, University of Helsinki, for public examination in Auditorium XII, University Main Building, on the 12th of December 2014 at 12 noon.

Helsinki 2014
To my family
Abstract

Cranial cruciate ligament (CCL) disease is one of the most common causes of lameness in dogs. Surgical treatment is recommended to stabilize the stifle joint, alleviate pain, and delay the progression of osteoarthritis (OA). A variety of surgical techniques has been introduced and can be broken down into the more traditional intracapsular ligament replacement and extracapsular suture techniques and the newer neutralizing dynamic osteotomy techniques. Although an enormous amount of literature is available concerning this disease, surprisingly few studies have assessed surgical outcome with objective evaluation methods and comparison between groups. Previous studies have demonstrated significant improvement of limb function after CCL surgery. However, OA has been shown to progress in most patients, and this may cause deterioration in the function of the surgically treated limb over time. Long-term follow-up studies that include objective evaluation methods designed for assessing orthopedic outcome are needed.

This thesis aimed to evaluate the long-term surgical outcome and signs of chronic pain after CCL surgery. Also, outcomes between the intracapsular, extracapsular and osteotomy techniques were compared. A multimodal approach, including an owner questionnaire and assessment of chronic pain using the validated Helsinki Chronic Pain Index (HCPI), orthopedic and radiographic examinations, force plate analysis, and as a new evaluation method, a physiotherapeutic examination was included. To provide reference values, clinically healthy Rottweilers and Labrador Retrievers were examined.

A long-term retrospective follow-up with a mean time interval of at least 2.7 years between the surgery and evaluation was conducted. Of the 206 surgically treated dogs that were evaluated by their owners, 31.1% had a HCPI value ≥ 12, indicating pain. Of the 47 dogs evaluated by a veterinarian 31.9% showed a pain response to flexion/extension of the surgically treated joint. In addition to the unilaterally treated CCL rupture, contralateral stifle joint pathology and other orthopedic problems were frequently diagnosed during the evaluation. When symmetry of weight bearing was evaluated in dogs with no other orthopedic findings (n=21), approximately 30% of dogs had decreased dynamic and static weight bearing in the surgically treated limbs. Also, goniometric angles of the surgically treated limbs remained inferior to those of healthy limbs, and impairment of active range of motion was frequently observed.

The owner assessments revealed no significant differences between the surgical techniques in long-term outcome. However, differences were seen in clinical evaluation of dynamic and static weight bearing between intracapsular and osteotomy technique groups. Although the retrospective study design and low sample size have to be acknowledged and may cause bias to the results, osteotomy techniques may offer long-term limb function that is superior to that achieved with the intracapsular technique. The low number of dogs treated with the extracapsular technique did not allow comparison of dynamic or static weight bearing to other technique groups.
List of original publications

This thesis is based on the following publications:


These publications are referred to in the text by their Roman numerals.

The original publications have been reprinted with the kind permission of their copyright holders. In addition, some unpublished material has been presented.
Acknowledgments

This study was carried out at the Department of Equine and Small Animal Medicine, Faculty of Veterinary Medicine, University of Helsinki, Finland. The patient material was gathered in cooperation with the Veterinary Teaching Hospital of the University of Helsinki and the private orthopedic referral clinics of Espoon eläinsairaala, Finnin Ratsutila ja Eläinlääkkötä, HauMau, Malmin eläinklinikka Apex, and Mevet.

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Abbreviations

ANCOVA  analysis of covariance
ANOVA  analysis of variance
AROM  active range of motion
ASI  asymmetry index
AvFS  average falling slope
AvRS  average rising slope
Break imp  breaking impulse
Break peak  breaking peak force
Break time  breaking time
BrOAD  Bristol Osteoarthritis in Dogs
CaCL  caudal cruciate ligament
CBPI  Canine Brief Pain Inventory
CCL  cranial cruciate ligament
COI  Canine Orthopedic Index
CPL  contralateral pelvic limb
CTL  contralateral thoracic limb
CTWO  cranial tibial wedge osteotomy
CVWO  chevron wedge osteotomy
Degr  degree
Diff SWB%  difference in quantitatively measured SWB% between hind limbs
DPVF  distribution percentage per limb of peak vertical force
Ext  extracapsular technique
Funct  functional limb length
g  gravitational acceleration
h  functional limb length
HCPI  Helsinki Chronic Pain Index
Int  intracapsular technique
ITL  ipsilateral thoracic limb
L  left
MDS  multifactorial descriptive scale
meSWB  manually evaluated static weight bearing
MRI  magnetic resonance imaging
NA  not analyzed
NE  not evaluated
NRS  numerical rating scale
NSAID  nonsteroidal anti-inflammatory drug
OA  osteoarthritis
Ost  osteotomy technique
PL  pelvic limb
PROM  passive range of motion
Prop imp  propelling impulse
Prop peak  propelling peak force
Prop time  propelling time
PTIO  proximal tibial intra-articular osteotomy
PVF  peak vertical force
<table>
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<th>Description</th>
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<tr>
<td>PVF time</td>
<td>time to peak vertical force</td>
</tr>
<tr>
<td>qmSWB</td>
<td>quantitatively evaluated static weight bearing</td>
</tr>
<tr>
<td>R</td>
<td>right</td>
</tr>
<tr>
<td>ROM</td>
<td>range of motion</td>
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<tr>
<td>SD</td>
<td>standard deviation</td>
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<tr>
<td>SDS</td>
<td>simple descriptive scale</td>
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<td>SI</td>
<td>symmetry index</td>
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<td>STPL</td>
<td>surgically treated pelvic limb</td>
</tr>
<tr>
<td>SWB</td>
<td>static weight bearing</td>
</tr>
<tr>
<td>SWB%</td>
<td>quantitatively measured static weight bearing as percentage of body weight</td>
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<tr>
<td>TC</td>
<td>thigh circumference</td>
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<tr>
<td>TL</td>
<td>thoracic limb</td>
</tr>
<tr>
<td>TPLO</td>
<td>tibial plateau leveling osteotomy</td>
</tr>
<tr>
<td>TTA</td>
<td>tibial tuberosity advancement</td>
</tr>
<tr>
<td>TTO</td>
<td>triple tibial osteotomy</td>
</tr>
<tr>
<td>v</td>
<td>velocity</td>
</tr>
<tr>
<td>VAS</td>
<td>visual analog scale</td>
</tr>
<tr>
<td>VI</td>
<td>vertical impulse</td>
</tr>
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<td>Vrel</td>
<td>relative velocity</td>
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1 Introduction

Cranial cruciate ligament (CCL) rupture is the leading cause of hind limb lameness and one of the most common orthopedic conditions in stifl e joints of dogs (Whitehair et al. 1993, Johnson et al. 1994, Duval et al. 1999). It results in instability of the stifl e joint and leads to development of progressive osteoarthritis (OA) (Elkins et al. 1991, Innes and Barr 1998a). The cause for the disease remains unclear and is multifactorial. The disease is often bilateral, and many patients suffer from concurrent meniscal tears (Bennett and May 1991, Doverspike et al. 1993). Surgical treatment is currently recommended to stabilize the stifl e joint, alleviate the pain, and delay the progression of OA.

A variety of techniques has been developed for repair of CCL rupture, and new technique modifications are constantly emerging. Surgical techniques can be broadly classified into the traditional intracapsular ligament replacement and extracapsular suture techniques and the newer neutralizing dynamic osteotomy techniques (Piermattei et al. 2006). The large number of techniques indicates that no single technique is universally accepted, and the surgical technique is often chosen based on the surgeon’s personal preference and clinical experience. The use of intracapsular autograft techniques has strongly decreased in CCL repair during the last decade as the newer osteotomy techniques have gained popularity (Leighton 1999, Comerford et al. 2013, Duerr et al. 2014). However, concurrently, the surgical procedures have become technically more demanding and invasive, with increasing potential for surgical complications and a rising cost of procedures (Pacchiana et al. 2003, Hoffmann et al. 2006, Stauffer et al. 2006).

The evaluation of surgical outcome of veterinary orthopedic patients is challenging. Surgical outcome after CCL repair has been examined by using owner assessment, veterinary evaluation, radiography, and force plate analysis, and a vast number of studies have been published. The prevailing general opinion is that dogs recover more quickly and reach better surgical outcome when treated with osteotomy than with traditional techniques. However, clinical studies have failed to consistently prove the superiority of any single surgical technique over another. Recently, an effort has been made to design and conduct prospective studies with objective outcome assessment and comparative aspects (Conzemius et al. 2005, Au et al. 2010, Böddeker et al. 2012, Gordon-Evans et al. 2013, Nelson et al. 2013). However, most reports evaluating surgical outcome consist of a description of a single surgical technique, postoperative complications, and a subjective evaluation of surgical outcome without any comparison to healthy animals or animals treated with other techniques.

In the majority of dogs, limb function has been shown to improve significantly after CCL surgery. However, regardless of the surgical technique chosen, OA of the stifl e joint often progresses (Elkins et al. 1991, Hoffman et al. 2006, Au et al. 2010). Long-term follow-up (>1 year) studies, including objective outcome evaluation methods, are needed to determine the impact of advancing OA on a dog’s clinical condition over time.

The primary focus of this thesis was to evaluate the overall long-term surgical outcome and signs of chronic pain after CCL surgery. The secondary aim was to compare outcomes between the intracapsular, extracapsular, and osteotomy techniques. The assessment included force plate analysis and the validated Helsinki Chronic Pain Index (HCPI) as objective outcome evaluation methods and, as a new aspect, a physiotherapeutic evaluation conducted by a professional veterinary physiotherapist. Reference values were obtained from healthy Rottweilers and Labradors.
2. Review of the literature

2.1 Anatomy and function of the stifle joint

The stifle joint is a complex condylar synovial joint (Figure 1). The primary types of motion in the stifle joint are flexion-extension and rotation. The roller-like convex condyles of the femur articulate with the flattened condyles of the tibia and form the primary weight-bearing femorotibial part of the joint. At the cranial surface of the femur, the wide, smooth, grooved femoral trochlea articulates with the patella, forming the femoropatellar part of the joint. The role of the femoropatellar joint is to improve the efficiency of the extensor mechanism by increasing the moment arm of the quadriceps muscles. The proximal tibiofibular joint is the third component of the stifle joint. In addition to the patella, three smaller sesamoid bones are situated in the stifle region. The lateral and medial fabellae are located in the lateral and medial heads of the origin of the gastrocnemius muscle and the popliteal sesamoid bone within the tendon of origin of the popliteus muscle (Evans 1993, Carpenter and Cooper 2000).

2.1.1 Cranial and caudal cruciate ligaments

The primary ligamentous support to the stifle joint is provided by four femorotibial ligaments: two collateral ligaments and two cruciate ligaments. The cruciate ligaments are intra-articular but covered by synovium, and thus, extrasynovial (Evans 1993). They are composed of a core region that contains collagen fibrils and fibroblasts and an outer epiligamentous region of synovial intima (Hayashi et al. 2003). The cruciate ligaments are named based on their tibial attachments. The cranial cruciate ligament (CCL) originates from the caudomedial aspect of the lateral femoral condyle and the caudolateral part of the intercondylar fossa of the femur and runs diagonally in a craniomedial direction across the intercondylar fossa, spiraling outward axially to attach to the cranial intercondylar area of the tibia. The CCL is further divided into a larger caudolateral and a smaller craniomedial part. The caudal cruciate ligament (CaCL) originates from the lateral surface of the medial femoral condyle and runs caudodistally, spiraling inward to attach to the medial edge of the popliteal notch of the tibia (Heffron and Campbell 1978, Evans 1993).

The main function of the CCL is to limit the cranial tibial translation with respect to the femur; the CaCL is the primary restraint against the caudal tibial translation. The CCL and CaCL prevent hyperextension and limit internal rotation of the stifle joint. Together with collateral ligaments, they participate in limiting the varus and valgus angulations of the stifle joint (Arnoczky and Marshall 1977, Monahan et al. 1984). Also, by modulating major muscle groups involving the stifle, a complex system of mechano- and proprioceptors and reflex arcs takes part in limiting excessive joint motion (Arcand et al. 2000, Solomonow et al. 1987).
2.1.2 Menisci

Disks of fibrocartilage, the medial and lateral menisci, are located between the femoral and tibial condyles. Menisci are crescent-shaped bands of cartilage that are triangular in cross-section. They adapt to femoral and tibial articulating surfaces, thus improving joint congruity (Evans 1993). Menisci contribute to load bearing, load transmission, and energy absorption in the joint, decrease friction between the joint tissues, and provide rotational and varus-valgus stability to the joint (Walker and Erkman 1975, Krause et al. 1976, Levy et al. 1982, Pozzi et al. 2008). Ligaments and soft tissue attachments to the tibia and femur hold the menisci in place. The medial meniscus is more firmly attached to the tibia than the lateral meniscus (Evans 1993, Carpenter and Cooper 2000).

2.2 Pathogenesis of cranial cruciate ligament disease

CCL disease causes instability of the stifle joint due to cranial subluxation of the tibia in relation to the distal femur. The disease process is associated with synovitis, articular cartilage degeneration, periarticular osteophyte development, and capsular fibrosis, resulting in stifle OA (Marshall and Olsson 1971, Elkins et al. 1991, Vasseur and Berry 1992, Innes and Barr 1998a, Innes et al. 2000). The menisci, especially the less mobile caudal horn of the medial meniscus may become entrapped under the sliding motion of the femoral condyle, resulting in secondary meniscal tears (Bennett and May 1991). The etiology of CCL disease is multifactorial and complex, and despite decades of research, the pathological mechanisms behind the disease remain poorly understood.

In a vast majority of patients, CCL rupture is caused by a chronic degenerative process that leads to partial or complete tearing of the ligament, usually during the dog’s normal daily activities. In 40-50% of the dogs, the contralateral CCL ruptures within 5-17 months of the first one (Doverspike et al. 1993, Buote et al. 2009). The patient’s abnormal conformation or gait, age-
related changes, obesity or lack of fitness, and immune-mediated as well as genetic factors have been implicated as potential causes for ligament degeneration.

CCL rupture can occur in a wide variety of dog breeds. The most commonly affected breeds are Rottweilers, Labrador Retrievers, Newfoundland and Saint Bernhard Dogs, Mastiffs, and Staffordshire Bull Terriers (Whitehair et al. 1993, Duval et al. 1999), and therefore, a genetic background for the disease has been suspected. Heritability of CCL rupture was studied in Newfoundland Dogs, and a recessive mode of inheritance with 51% penetrance was proposed (Wilke et al. 2006). The strength of the CCL has been shown to deteriorate with age (Vasseur et al. 1985). These changes and also clinical signs of CCL rupture develop earlier in breeds of larger size, whereas smaller dogs tend to be affected later in life (Vasseur 1984, Vasseur et al. 1985, Bennett et al. 1988, Whitehair et al. 1993). Neutered dogs, whether male or female, have a higher prevalence of CCL rupture than sexually intact dogs (Whitehair et al. 1993, Duval et al. 1999).

The association of CCL rupture with conformational factors of pelvic limbs and stifl e joints has been evaluated in many studies. Bowlegged (genu varum) or “straight” stance conformations and medial patellar luxations have been traditionally regarded as risk factors for CCL rupture (Johnson and Johnson 1993, Moore and Read 1996, Gibbons et al. 2006). The narrowed conformation of the intercondylar notch has been diagnosed in dogs with CCL disease and also in Retrievers predisposed to CCL deficiency, potentially resulting in impingement and wear of the CCL (Vasseur and Berry 1992, Aiken et al. 1995, Comerford et al. 2006, Lewis et al. 2008). High tibial plateau angle was proposed as a risk factor in a study by Morris and Lipowitz (2001), but other studies have not been able to confirm this finding (Wilke et al. 2002, Reif and Probst 2003). Mean tibial plateau angles in clinically normal dogs have been reported to range from 18° to 24° (Morris and Lipowitz 2001, Wilke et al. 2002, Reif and Probst 2003).

The role of exercise in the pathogenesis of CCL degeneration remains unclear. Obesity, immobilization, and poor physical condition have been suspected to predispose to CCL rupture by increasing the load to the ligaments and decreasing the condition of the thigh muscles involved in protecting the CCL from excessive strain (Solomonow et al. 1987, Johnson and Johnson 1993, Moore and Read 1996). On the other hand, overuse and fatigue changes due to repetitive overloading have been proposed to be associated with ligament rupture (Hayashi et al. 2003). Recently, also abnormal neuromuscular control of hamstring muscles was suggested to play a causal role in the progression of CCL disease (Hayes et al. 2013). Finally, the role of immunologic factors in CCL disease has been evaluated in many studies. However, controversy remains whether the inflammatory changes are primary contributors or secondary consequences to CCL disease (Doom et al. 2008, Comerford et al. 2011).

In a minority of patients, CCL rupture is purely traumatic and results from overloading the ligament, typically when the animal falls or jumps from high or when the limb becomes caught in a hole or fence. In adult dogs, this injury usually results in a midsubstance “mop end” tear of the CCL. In skeletally immature dogs, the attachment of ligament to bone may be materially stronger than the bone itself, resulting in an avulsion fracture of the ligament from its femoral or, more commonly, tibial attachment site (Moore and Read 1996, Piermattei et al. 2006).
2.3 Diagnostics of cranial cruciate ligament disease

2.3.1 Orthopedic examination

CCL disease causes hind limb lameness, which may vary from non-weight-bearing lameness in acute, complete tears to mild exercise-induced lameness in more chronic or partial tears. The typical palpatory changes are joint effusion, pain response to flexion and extension of the joint, and, in more chronic cases, crepitation and periarticular fibrous tissue development or “medial buttress” in the medial side of the joint. The pain and disuse of the limb causes atrophy of the thigh muscles. The possible concurrent meniscal tear may induce a clicking sound when the joint is moved through its range of motion. Cranial drawer test and tibial compression test are pathognomonic clinical tests for complete CCL rupture. They both induce abnormal cranial tibial subluxation in relation to the distal femur. In partial CCL tears, however, the abnormal movement may be more subtle or absent, depending on which part or parts of the CCL are torn (Piermattei et al. 2006, Kowaleski et al. 2012).

2.3.2 Diagnostic imaging

Even though the CCL rupture itself is usually not visible in stifle radiographs, radiographic examination of the stifle joints is recommended for all patients to verify the pathology of the joint and to rule out other concurrent diseases. Typical radiographic findings comprise osteoarthritic changes in the joint. Depending on the chronicity of the disease, joint effusion with typical loss of infrapatellar fat pad shadow and osteophyte and enthesiophyte formation within the cranial intercondylar area of the tibia, the femoral trochlear ridges, the tibial condyles, the base and apex of the patella, and the intercondylar notch of the femur accompanied by subchondral sclerosis are seen (Marshall and Olsson 1971, Widmer et al. 1994). In addition to radiography, magnetic resonance imaging (MRI), ultrasonographic examination, and thermal imaging have been evaluated and found useful in diagnosing CCL ruptures and meniscal tears (Marino and Loughlin 2010). However, these imaging modalities usually require specialized instrumentation, advanced training, and practice to be successful.

2.3.3 Arthroscopy

Arthroscopy is considered the golden standard of joint evaluation and allows a thorough inspection of the synovium, articular cartilage, cruciate ligaments, and menisci with magnification. Arthroscopic examination can be used to diagnose early lesions of cruciate ligaments, to confirm pathology in uncertain cases, to evaluate the menisci for secondary meniscal lesions, and to facilitate concurrent treatment of the findings (Siemering 1978, Whitney 2003).

2.4 Conservative treatment of cranial cruciate ligament disease

Conservative nonsurgical treatment of CCL rupture includes weight loss, medication such as nonsteroidal anti-inflammatory drugs (NSAIDs) or nutraceuticals, physiotherapy, and controlled exercise. The outcome of conservative treatment has not been extensively investigated. In two retrospective studies, nonsurgical management was reported to result in satisfactory function in the majority of small dogs (<15-20 kg), whereas lameness persisted in larger dogs, necessitating surgical treatment for successful outcome (Pond and Campbell 1972, Vasseur 1984). Recently, a
prospective study was conducted to evaluate the outcome of surgical and nonsurgical treatment for overweight dogs with CCL rupture. Although the dogs treated surgically in addition to conservative management had better outcomes than the dogs treated with nonsurgical methods alone, almost two-thirds of the dogs in the nonsurgical treatment group had a successful outcome one year after initiation of treatment (Wucherer et al. 2013).

2.5 Surgical treatment of cranial cruciate ligament disease

Surgical treatment is advocated to stabilize the stifle joint, alleviate pain, treat any concurrent meniscal pathology, and decelerate the development of OA. Regardless of the surgical technique chosen, the stifle joint is usually evaluated via arthroscopy or arthrotomy to diagnose and treat possible concurrent meniscal pathology. In addition, most surgeons debride the remnants of the torn cruciate ligament with the intention of decreasing the inflammatory process maintained by a remaining cruciate ligament stump. Primary repair of the torn CCL is seldom possible. However, avulsion fractures of the CCL attachment sites in young animals can be treated with internal fixation (Piermattei et al. 2006, Kowaleski et al. 2012).

2.5.1 Intracapsular reconstruction techniques

Intracapsular reconstruction techniques comprise the oldest group of CCL repair methods, and these techniques also have a long tradition in Finland. Intracapsular techniques are considered the standard for CCL repair in humans (Hospodar and Miller 2009). In intracapsular reconstruction, the torn CCL is replaced with autogenous tissue, other biological material such as allografts, xenografts, synthetic material, or a combination of synthetic and biological materials by mimicking the normal anatomy and attachment points of the CCL. In dogs, the most widely used replacement material has been fascia lata and/or patellar ligament (Figure 2).

One of the first intracapsular techniques was developed by the Finn Saki Paatsama in the 1950s. In the "Paatsama" technique, the CCL is replaced with a strip of fascia lata, which is left attached distally. The graft is brought through the bone canals that are drilled in the tibia and femur at the anatomic insertion and origin of the CCL, tightened, and attached with sutures along the patellar ligament (Paatsama 1952).

In 1979, Arnoczky et al. described the "over-the-top" technique. In this technique, the replacement for CCL is harvested from the medial third of the patellar ligament, part of the patella and fascia lata. The graft is brought through the joint, over the top of the lateral condyle, and sutured. Significant injury to the patella may occur when harvesting the graft, but with this technique the risk for inaccurate placement of drill canals and fraying of the graft to bony edges of the drill canals can be avoided (Arnoczky et al. 1979). Several variations and modifications to these original techniques have since been introduced (Hulse et al. 1980, Hulse et al. 1983, Denny and Barr 1984, Shires et al. 1984, Denny and Barr 1987, Piermattei et al. 2006).

The goal of intracapsular reconstruction is that after phases of initial graft inflammation and necrosis the graft will revascularize, remodel, and begin to act as native CCL; achievement of this goal has been shown experimentally (Arnoczky et al. 1982). The process may, however, be slow or incomplete, leading to elongation and failure of the graft, with recurrent instability of the joint (Butler et al. 1983, Hulse et al. 1983). The continuing degenerative process related to the naturally occurring CCL disease also may affect the grafted tissue in a manner similar to native CCL. Inferior strength properties of the autograft relative to native CCL can also decrease the
chances of graft survival under load. Unlike in humans, none of the tissues around the stifl e joint in dogs approaches the strength of the native CCL (Johnson et al. 1989).

Replacement of the CCL with allografts or xenografts has been evaluated in experimental studies, but these materials have not yet been used in clinical canine patients (Curtis et al. 1985, Arnoczky et al. 1986, McMaster 1994). Such disadvantages as tissue availability, potential disease transmission, negative impact of graft sterilization or radiation, and immune reactions have limited the development of allograft or xenograft techniques (Kowaleski et al 2012). In studies evaluating synthetic materials, permanent prosthetic grafts have mostly failed due to mechanical failure in both humans and dogs (Gupta and Brinker 1969, Rubin et al. 1975, Denny and Goodship 1980, Legnani et al. 2010). In addition, the use of autografts combined with synthetic material as an augmentation device and materials that have the ability to allow and promote tissue ingrowth have been evaluated in both humans and dogs (Park et al. 1985, Laitinen 1994, Legnani et al. 1010). Although some studies have shown promising early results, many techniques have been unsuccessful due to eventual failure of the graft and long-term results are needed. Current research appears to be focusing on tissue engineering and development of scaffolds that support tissue ingrowth for neoligamentization but gradually resorb to allow progressive loading of the new ligament.

2.5.2 Extracapsular stabilization

Extracapsular stabilization covers a variety of stabilization methods in which the craniocaudal instability is eliminated using extra-articular prostheses, usually sutures. These include imbrication techniques, fabellotibial suture techniques, the TightRope CCL technique, and
fibular head transposition. These techniques rely on development of periarticular fibrous tissue to provide long-term stability because the primary implants tend to fail over time.

The first extracapsular stabilization procedures in the 1960s were done by tightening of the stifle joint with Lembert sutures placed on the lateral retinacular fascia of the joint. DeAngelis and Lau (1970) modified the technique by providing anchorage points to the suture: proximally, the dense connective tissue caudoproximal to the lateral fabella, and distally, the patellar tendon. Further modifications of the technique consisting of changes in anchorage points and number of sutures were described by Flo (1975), Gambardella et al. (1981), and Brinker et al. (1990). Smith and Torg presented the fibular head transposition technique in 1985. In this technique, the fibula was advanced cranially, thus altering the orientation of the lateral collateral ligament and eliminating the cranial drawer.

The most commonly used extracapsular stabilization method today is the “fabellotibial suture” technique, again a modification of the technique by DeAngelis and Lau (1970) (Figure 3). In this technique, the craniocaudal instability is eliminated by using heavy nonabsorbable suture material, usually nylon leader line, nylon fishing line, or braided polyester sutures inserted and tensioned between the tibial tuberosity and the lateral fabella. To prevent slipping of the suture, it is placed in the fibrous origin of the lateral head of the gastrocnemius, slightly proximal to the fabella. The suture is passed through the hole predrilled in the tibial crest and under the patellar ligament from the medial to the lateral side, to complete the mattress suture. Alternatively, two holes can be made in the tibial tuberosity. The mattress suture is tensioned to neutralize the cranial drawer and fastened by knots or a tensioning device and a metallic crimp tube. In order to tighten the soft tissues and induce periarticular fibrosis, imbricating suture patterns are

Figure 3 Extracapsular stabilization using a fabellotibial suture (left) or a suture and bone anchor (right).
used to close the fascia and the joint capsule in cases where the joint is inspected via arthrotomy (Kowaleski et al. 2012). Minimally invasive modification of the fabellotibial suture technique has been described (Hoelzler et al. 2004, Biskup and Griffon 2014).

Recent attention has been focused on isometry of the tibial and femoral suture anchorage points (i.e. maintaining a consistent distance between the points during the stifle range of motion). The anchorage points used in the traditional fabellotibial suture technique were reported to be nonisometric, and this was shown to cause tightening and loosening of the suture during the stifle range of motion (Hulse et al. 2010). Although determination of a truly isometric combination of anchorage points may not be possible, near-isometric locations for the anchorage have been proposed (Roe et al. 2008, Hulse et al. 2010), and technique modifications aimed at a more isometric suture insertion by using suture anchors or bone tunnels have been reported (Guénégo et al. 2007, Kunkel et al. 2009) (Figure 3). Moreover, the latest modification of extracapsular techniques, the TightRope CCL technique, achieves stabilization by using a flat, braided polyethylene polyester tape that is anchored to near-isometric locations via femoral and tibial bone tunnels and suture buttons (Cook et al. 2010a).

The proposed advantages of the fabellotibial suture technique include technical ease of the procedure, minor surgical trauma, no requirement for specialized instrumentation, a shorter surgical time than in many other techniques, and thus, also a reasonable surgical cost. Inability to anchor or secure the suture loop adequately may predispose to slipping of the suture from the fabella, elongation or failure of the suture too early, resulting in recurrent instability (Tonks et al. 2011). With bone suture anchors or bone tunnels, a near-isometric anchorage is achieved and problems related to circumfabellar suture placement are avoided, although pullout of the anchors from the femoral bone has been reported (Guénégo et al. 2007). In addition to these, a minimally invasive approach is used in the TightRope technique (Cook et al. 2010a).

### 2.5.3 Osteotomy techniques

Osteotomy techniques are based on an approach that is very different from the traditional intracapsular and extracapsular stabilization methods. In osteotomy techniques, the aim of the surgical procedure is to achieve functional stability of the stifle joint during weight bearing. Unlike in the traditional surgical techniques, the passive function of the CCL is not restored.

The biomechanical rationale for the osteotomy techniques was introduced and modified by Slocum in 1983 and 1993, respectively, and later criticized by Tepic in 2002. Slocum described the total tibiofemoral joint force of weight bearing to be oriented parallel to the axis of the tibia and to be divided into components of a cranial tibial thrust force oriented parallel to the tibial plateau and a joint compressive force oriented perpendicular to the tibial plateau. Due to the caudodistally directed slope of the tibial plateau, limb loading results in a cranial tibial shear force and the magnitude of this shear force is dependent on the steepness of the tibial plateau slope. Based on Slocum’s “Active Model of the Stifle”, the joint stability in a normal joint is achieved by synergism between the stifle joint flexors and extensors. The cranial tibial thrust force is balanced by the pull of the stifle flexor muscles of the thigh and the passive restraints of the stifle joint including the CCL and the caudal horn of the medial meniscus. However, in the CCL-deficient joint the cranial tibial thrust force causes cranial tibial subluxation during limb loading. By reducing the tibial plateau angle surgically, this cranially oriented shear force can be eliminated (Slocum and Devine 1983, Slocum and Devine Slocum 1993).
Based on Slocum’s findings, the first osteotomy technique, cranial tibial closing wedge osteotomy (CTWO), was described in 1984 (Slocum and Devine 1984). In the CTWO technique, the tibial plateau angle is reduced by using a cranially based wedge osteotomy of the proximal tibia. The second osteotomy technique, tibial plateau leveling osteotomy (TPLO) was introduced in 1993 (Slocum and Devine Slocum 1993) (Figure 4). In the TPLO, the slope of the tibial plateau is reduced by a crescent-shaped osteotomy of the proximal tibia using a biradial saw blade. Subsequent rotation of the proximal segment aims at achieving a postoperative tibial plateau angle of 5°. The amount of rotation is calculated based on the preoperative tibial plateau angle and the radius of the osteotomy. Internal fixation with a TPLO plate and conventional or locking screws is used to support the new position of the proximal bone segment (Slocum and Devine Slocum 1993, Kowaleski et al. 2012).

**Figure 4** Tibial plateau leveling osteotomy.

The TPLO alters the biomechanics of the tibiofemoral joint, but maintains the original position of the femoropatellar joint and the tibial tuberosity (Slocum and Devine Slocum 1993). The TPLO has been shown to neutralize the cranial tibial subluxation in CCL-deficient stifles in vitro (Warzee et al. 2001, Reif et al. 2002, Kim et al. 2009a), but the results were more inconsistent when the effect of TPLO on femorotibial subluxation was evaluated in vivo during standing (Kim et al. 2012). Secondary to altered biomechanics, the TPLO may cause increased strain to the extensor mechanism of the stifle (Carey et al. 2005). The TPLO technique requires specialized instrumentation and is technically more demanding and a more invasive procedure than most of the other CCL repair methods, which is mirrored in the higher cost of the procedure.

In 2002, Tepic et al. suggested that the compressive forces of weight bearing are not axially oriented, but are directed parallel to the patellar tendon. According to this, the cranial tibial thrust force depends on the angle between the tibial plateau and the patellar tendon. It was also suggested that if the patellar tendon is oriented perpendicular to the tibial plateau the cranial shear component of the joint force is eliminated (Tepic et al. 2002). This led to the development
of the tibial tuberosity advancement (TTA) technique (Montavon et al. 2002) (Figure 5). The aim of the TTA technique is to eliminate the cranial tibial thrust by reducing the angle between the patellar tendon and the tibial plateau to 90°. Normally, this angle is 105° when the stifle is extended to 135°. A longitudinal osteotomy is made subjacent to the tibial tuberosity, and the tibial tuberosity is advanced cranially with a spacer-cage inserted proximally between the osteotomy. A tension-band bone plate is inserted to support the new position, and a bone graft is applied to the osteotomy space to accelerate bone union. The amount of advancement and the size of the cage needed are determined based on preoperative radiographic measurements (Montavon et al. 2002). An excessive tibial plateau angle may be a contraindication for TTA, with an anecdotally proposed cut-off point of 30°.

The TTA technique is generally considered less invasive and technically less demanding than the other tibial osteotomies. Like in TPLO, special instrumentation is needed and a number of surgical errors may occur. The TTA maintains the original position of the femorotibial articulation, thus having less effect on load transmission across the joint than TPLO (Kim et al. 2009b, Guerrero et al. 2011). However, a recent in vivo study showed that, similar to TPLO, TTA did not consistently restore femorotibial stability during standing, and two-thirds of the dogs had persistent subluxation after surgery (Skinner et al. 2013).

TPLO and TTA are the most commonly used osteotomy techniques and their popularity has increased enormously during the last decade. In addition, several technique modifications developed to overcome certain limitations related to the above-mentioned techniques include a triple tibial osteotomy (TTO) (Bruce et al. 2007), a combination of TPLO and CTWO (Talaat et al. 2006), a proximal tibial intra-articular osteotomy (PTIO) (Damur et al. 2003, Jerram et al. 2005), and the chevron wedge osteotomy (CVWO) (Hildreth et al. 2006). In the TTO technique, the longitudinal partial osteotomy of the tibial tuberosity is combined with a partial wedge osteotomy of the tibia. The reduction of the wedge osteotomy decreases the tibial plateau...
slope and simultaneously shifts the tibial tuberosity cranially (Bruce et al. 2007) (**Figure 6**). The proposed advantages of the TTO include minimal change in the orientation of the articulating surfaces of the tibiofemoral joint, no loss of limb length, and, unlike in TTA, a small osteotomy gap caudal to the tibial tuberosity. However, despite using recommended surgical calculations, unpredicted variation of the postoperative patellar tendon to the tibial plateau angle has been reported (Bruce et al. 2007).

Recently, a proximal tibial epiphysiodesis was described for treatment of CCL rupture in young dogs with open growth plates either as a sole treatment or to augment primary repair of CCL avulsion fracture. The tibial osteotomy is not done, but a premature union of the cranial tibial epiphysis is surgically induced while the caudal physis continues to grow, resulting in a reduction of the tibial plateau angle (Vezzoni et al. 2008).

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**2.5.4 Complications after surgical treatment**

Scant information is available on complication types and rates associated with intracapsular autograft techniques. Although many reports have been written on different technique modifications of extracapsular repair and differences in properties of suture materials and methods of securing sutures, only one report concentrating on complications after the fabellotibial suture technique has been published. In this report, complications occurred in 17.4% of procedures and included incisional problems, wound infection, peroneal nerve damage, implant-related problems, and late meniscal tears (Casale and McCarthy 2009). A second surgery was required in 7.2% of patients. The postoperative infection rate after fabellotibial suture stabilization reported in two studies was 3.9% and 4.2% of patients, respectively (Casale and McCarthy 2009, Frey et al. 2010). Two studies have reported complications of TightRope
technique in 17.8% and 29.2% of procedures, including implant failure, seroma, infection, and late meniscal tears (Cook et al. 2010a, Cristopher et al. 2013). In 8.9% and 12.5% of the procedures, respectively, the complications were major, requiring further treatment.

Numerous intra- and postoperative complications have been described in dogs undergoing osteotomy procedures. The highest complication rates were reported in studies documenting initial experience with the techniques, and the number of complications has tended to decrease as more knowledge has been gained. The complications related to TPLO surgery have been thoroughly reported. The overall complication rates ranging between 15% and 28% have included incisional problems (edema, discharge, seroma, dehiscence), infection, tibial tuberosity fracture, implant failure, patellar tendonitis, osteomyelitis, late meniscal tears, fibular fracture, and patellar fracture (Pacchiana et al. 2003, Priddy et al. 2003, Kergosien et al. 2004,斯塔弗 et al. 2006, Fitzpatrick and Solano 2010, Gatineau et al. 2011, Christopher et al. 2013). After TTA surgery, reported complication rates have varied substantially, ranging from 10% to 59%. As in TPLOs, incisional problems, infection, tibial tuberosity fracture, implant failure, and late meniscal tears have been the most common (Hoff man et al. 2006, Lafaver et al. 2007, Steinberg et al. 2011, Wolf et al. 2012). After TTO surgery, complications have been reported to occur in 23-36% of patients (Bruce et al. 2007, Moles et al. 2009).

Although overall complication rates are commonly reported, differences between reports in description and classification of the complications make direct comparison of the surgical techniques difficult. In the study by Christopher et al. (2013), the complications were classified as catastrophic, major, and minor, according to the presently recommended criteria (Cook et al. 2010b). More major complications and late meniscal tears occurred after TTA surgery than after TPLO or TightRope techniques, and also after TPLO surgery than after the TightRope technique. However, as a study limitation it must be mentioned that only 18 of the 162 dogs were treated using the TTA technique. When individual complication types are evaluated, patellar tendonitis seems to occur less often after TTA than after TPLO surgery, probably due to the lower strain on the extensor mechanism (Tepic 2002). Incisional problems, such as postoperative edema, discharge, bruising, and seroma formation, appear more frequently after osteotomy procedures than after other techniques, likely due to the more invasive approach. The reported postoperative infection rates after osteotomy procedures have varied between 2.9% and 8.4% (Priddy et al. 2003, Hoffmann et al. 2006, Fitzpatrick and Solano 2010, Frey et al. 2010, Gatineau et al. 2011), and infection occurs more often after TPLO than after extracapsular stabilization (Frey et al. 2010).

### 2.5.5 Treatment of menisci


Although meniscal damage usually results from joint instability associated with CCL rupture, meniscal tears may also occur as a late complication after stabilization procedures (Case et al. 2008). Late meniscal tears have been suggested to occur especially after osteotomy procedures in which passive laxity of the joint is not addressed. Originally introduced by Slocum
for use with the TPLO technique, a meniscal release procedure is advocated to decrease the risk of these late tears. The meniscus is sharply cut either at the caudal meniscotibial ligament or at the midbody of the medial meniscus to allow caudal displacement of the caudal horn of the medial meniscus, thus preventing it from being entrapped under the femoral condyle (Slocum and Devine Slocum 1998). However, recent in vitro studies have proven that the meniscal release procedure also has negative influences and actually has effects similar to caudal medial hemimeniscectomy with regard to meniscal load transmission function (Pozzi et al. 2008, Pozzi et al. 2010). The effects of meniscal release were also evaluated in vivo in CCL-intact stifle joints, where the meniscal release procedure alone was reported to cause lameness, articular cartilage loss, further meniscal pathology, and osteoarthritic changes (Luther et al. 2009).

2.6 Outcome assessment after cranial cruciate ligament surgery

The assessment of surgical outcome after CCL repair has traditionally been based on a veterinarian’s or an owner’s opinion of lameness and surgical outcome and measurement of radiographic OA in the surgically treated limb. With this kind of simple and often qualitative assessment, the outcome evaluation has been very subjective. Only recently, as general awareness of the need for quantitative and more objective outcome assessment has increased, such objective outcome methods as force plate analysis or validated owner-assessment tools have become more available and routinely included also in studies reporting outcome after CCL surgery.

2.6.1 Owner evaluation

Although owner evaluation is subjective, owners have the advantage of being able to evaluate the dogs’ function during its daily activities, in its own unstressful environment over time. The owner’s opinion of the surgical outcome has long been ascertained with simple questions regarding surgical outcome, dog’s quality of life, and owner’s satisfaction with the surgical procedure and willingness to have it repeated if necessary. High success rates (>90% of owners evaluating the surgical outcome as excellent or good) have been reported, regardless of the surgical technique used. Similarly, >90% of owners are usually satisfied with the surgical procedure and would have it performed on another dog with CCL injury.

Recently, more sophisticated and reliable owner-assessment methods have been developed for evaluation of OA and chronic pain in orthopedic patients (Innes and Barr 1998b, Hudson et al. 2004, Wiseman-Orr et al. 2006, Cimino Brown et al. 2007, Hercock et al. 2009, Helmbjörkman et al. 2009, Cimino Brown 2014a, Cimino Brown 2014b, Cimino Brown 2014c). Bristol Osteoarthritis in Dogs (BrOAD) questionnaire (Innes and Barr 1998b) and Texas A&M Client Questionnaire (Hudson et al. 2004) are validated visual analog scale (VAS)-based owner questionnaires, and Canine Brief Pain Inventory (CBPI) is a validated numeric rating scale (NRS)-based questionnaire (Cimino Brown et al. 2007). Several studies have used these questionnaires also to evaluate surgical outcome after CCL repair. In three studies reporting results using the BrOAD questionnaire, significant improvements in the levels of disability and inactivity stiffness, in the effect of cold weather, and in the ability to jump were seen after repair with intracapsular, TPLO, and TTO techniques (Innes et al. 2000, Corr and Brown 2007, Renwick et al. 2009). Similarly, Boyd et al. (2007) reported significant improvement in the summed scores of BrOAD questions in the postoperative evaluation after TPLO surgery. One of these studies also compared TPLO and CTWO techniques, and, unlike the TPLO, CTWO failed to produce
significant improvements in the level of inactivity stiffness and in the effect of cold weather (Corr and Brown 2007). On the other hand, another two studies found no significant differences in the outcome between the TPLO and TightRope techniques when the results on the Texas A&M questionnaire were compared (Cook et al. 2010) or between the TPLO and extracapsular techniques when the CBPI questionnaire was used (Gordon-Evans et al. 2013).

The Helsinki Chronic Pain Index (HCPI) is a validated pain index based on 11 MDS questions concerning a dog's mood, behavior, and locomotion, and, unlike the previous indices, it also takes into account the emotional aspect of pain (Hielm-Björkman et al. 2003, Hielm-Björkman et al. 2009, Walton et al. 2013). The HCPI has been used in the evaluation of chronic pain in dogs with hip, elbow, and stifle joint OA (Hielm-Björkman et al. 2003, Hielm-Björkman et al. 2009, Wernham et al. 2011, Eskelinen et al. 2012, Hielm-Björkman et al. 2012, Heikkilä et al. 2014). In the HCPI, the owner-reported answers in the 5-point descriptive scale are tied to a value (0-4), which when summed, yields a total index minimum score of 0 and maximum score of 44. Individual scores of 0 and 1 on each question indicate normal mood, behavior, and locomotion, and scores of 2, 3, and 4 indicate pain in ascending severity. Healthy dogs usually have an HCPI between 0 and 6, whereas values between 7 and 35 have been measured in dogs with chronic pain. However, healthy dogs may have index values up to 11, assuming that an individual score of 1 is considered normal. Thus, the index values between 6 and 11 are considered a gray zone where the dog may be either pain-free or in pain (Hielm-Björkman et al. 2003).

The newest investment in improving the quality of owner-reported outcome assessment is a multifactorial descriptive scale (MDS)-based questionnaire, the Canine Orthopedic Index (COI), which was recently validated (Cimino Brown et al. 2014a, Cimino Brown et al. 2014b, Cimino Brown et al. 2014c) but has not yet been established for evaluation of CCL patients.

### 2.6.2 Orthopedic examination

An orthopedic examination has traditionally been included in CCL outcome studies. Typically, it has consisted of a visual lameness evaluation using a simple descriptive scale (SDS), VAS, or varying NRS-based scores. Although often used, unfortunately, the visual evaluation has been found to be insensitive for detecting lameness (Evans et al. 2005, Quinn et al. 2007). Quinn et al. (2007) reported that both NRS- and VAS-based scores had low agreement among observers unless the lameness was severe. Also, if the lameness was not severe, the correlation with the results of force plate analysis was generally low. In addition to lameness evaluation, varying descriptions of the stifle joint palpatory findings and cranial drawer test have usually been included in the orthopedic examination.

Differences in grading scales, presentation methods, and follow-up times render the comparison of orthopedic examinations among studies difficult. In most studies, lameness has improved postoperatively and 73-94% of dogs have shown no visually detectable lameness at follow-up (DeAngelis and Lau 1970, Arnoczky et al. 1979, Gambardella et al. 1981, Denny and Barr 1987, Talaat et al. 2006, Guénégo et al. 2007, Lafaver et al. 2007, Moeller et al. 2010). Similar to owner assessments, usually >90% of veterinarians have described the surgical outcome as successful or satisfactory, using varying criteria.

Recently, also the quantitative measurements of stifle joint range of motion (ROM) and thigh muscle symmetry have been increasingly used (Jerram et al. 2005, Bruce et al. 2007, Jandi and Schultman 2007, Au et al. 2010, Kunkel et al. 2009, Moeller et al. 2010, Gordon-Evans et al. 2013, Oxley et al. 2013). Stifle joint ROM and thigh circumference (TC) have improved in
Review of the literature

almost all studies after surgery relative to the preoperative situation (Jerram et al. 2005, Bruce et al. 2006, Kunkel et al. 2009, Au et al. 2010, Gordon-Evans et al. 2013, Oxley et al. 2013). However, several studies have discovered that ROM and/or TC have started decreasing after more time has passed since surgery (Jerram et al. 2005, Bruce et al. 2007, Au et al. 2010, Gordon-Evans et al. 2013). Moreover, Moeller et al. (2010) reported that stifl e joint ROM and TC remained lower than in healthy control limbs in the long term. Surgical techniques have been compared in two studies after TPLO and extracapsular surgery and in one study after repair with TPLO and CTWO, all reporting equal outcomes, with no significant differences in goniometric or TC results between the techniques (Au et al. 2010, Gordon-Evans et al. 2013, Oxley et al. 2013).

According to my knowledge, the ROM or TC measurements have not been reported after repair with intracapsular, TightRope, or TTA techniques. Postoperative intensive physiotherapy has been shown to be beneficial for ROM and muscle mass (Monk et al. 2006).

2.6.3 Kinetic and kinematic evaluation

Compared with subjective visual lameness evaluation, force plate analysis allows quantitative measurement of dynamic weight bearing and can detect mild lameness or gait abnormality that may not be apparent during visual evaluation (Evans et al. 2005). In kinetic evaluation, peak vertical forces (PVFs) and vertical impulses (VIs) are the most commonly used parameters. Numerous factors can affect the generation of ground reaction forces during gait analysis. Of overall variance related to ground reaction force measurements, 29-85% was shown to be attributable to trial repetitions, 14-69% to dogs, and 0-7% to handlers (Jevens et al. 1993). Ground reaction forces can be measured at both trot and walk, but subject velocity has a significant effect on force plate values and must be limited to a narrow range when data are obtained (Riggs et al. 1993). Acceleration and deceleration during the trial must be controlled (Budsberg et al. 1999). Body weight of the dog affects the ground reaction forces, and to allow comparison of individual dogs or dog groups with different body weights, forces and impulses are usually expressed as a percentage of body weight. Recently, also the effect of body conformation on ground reaction forces has been considered (Bertram et al. 2000, Voss et al. 2010, Voss et al. 2011).

The best approach for outcome evaluation with force plate analysis is to compare the postoperative ground reaction forces with the pre-injury values. Unfortunately, this is usually impossible in clinical patients and can only be used in experimental studies. To compare the postoperative values with normal reference values, force plate data obtained from either healthy control dogs or the patient’s contralateral limb may be used. In comparison of the surgically treated limb with the contralateral limb, potential load distribution from the affected to the contralateral limb must be taken into account (Rumph et al. 1993). Alternatively, if ground reaction forces are compared with data obtained from healthy control dogs, factors like subject velocity, acceleration, and body weight should be carefully controlled.

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preinjury level is considered. In clinical patients with naturally occurring CCL disease, four studies have reported return of dynamic weight bearing to the level of healthy limbs (Budsberg et al. 1988, Böddeker et al. 2012, Nelson et al. 2013, Skinner et al. 2013). Budsberg et al. (1988) evaluated ground reaction forces in nine dogs before and after extracapsular repair with the modified retinacular imbrication technique and did not find any significant differences between affected and clinically normal pelvic limbs 7-10 months after surgery. More recently, a force plate treadmill was used to evaluate 14 dogs after repair using the TPLO technique, and by 4 months after surgery no significant differences could be seen between the affected and unaffected limbs (Böddeker et al. 2012). Also in a study by Nelson et al. (2013) the calculated symmetry indices (SIs) for PVF, VI, and contact time in 15 TPLO-treated dogs were not different from the control group by 6 months to 1 year postoperatively. However, only six dogs in the group completed the one-year follow-up. Finally, Skinner et al. (2013) evaluated clinical outcome in 26 TTA-treated dogs and found no significant difference between the surgically treated and contralateral limbs with a mean follow-up of 18 months.

Contrary to the previous studies, in several reports the ground reaction forces in surgically treated limbs or pelvic limb SIs have remained inferior to full function. Conzemius et al. (2005) evaluated 131 dogs that underwent surgery with intracapsular modified over-the-top, extracapsular fabellotibial suture, and TPLO techniques and compared the results with healthy control dogs. By 6 months, only 15% of dogs in the intracapsular, 14.9% in the extracapsular, and 10.9% in the TPLO group were judged to have normal limb function. As well, in a study evaluating postoperative limb function 4-16 months after TTA surgery in 37 dogs, PVF and VI remained significantly lower than in control group dogs, and in 64.3% of dogs the SI for PVF indicated residual lameness (Voss et al. 2008). In the study mentioned earlier, Böddeker et al. (2012) also reported that by 4 months after surgery, the 14 dogs treated with the extracapsular technique with a capsular-fascial imbrication method continued to have significantly lower force plate values in the affected limb than in the unaffected limb. Also Nelson et al. (2013) reported that after extracapsular fabellotibial suture repair the SIs in 16 dogs completing a one-year follow-up were lower than in control group dogs.

**Comparison of surgical techniques**

Few studies directly compare surgical techniques by using force plate analysis. In only one study has the intracapsular technique been compared with other repair methods (Conzemius et al. 2005). In this study, the dogs treated with the intracapsular technique had inferior limb function to the extracapsular and TPLO groups 2 and 6 months postoperatively, but no significant differences were found in ground reaction forces between the extracapsular and TPLO groups. Also in another study with a 2-year follow-up, no significant differences were found in PVFs between extracapsular repair and TPLO when treatment in both groups included postoperative physical rehabilitation. In this study, the PVF was measured using a pressure sensitive walkway (Au et al. 2010). By contrast, the results of three recent studies indicate that TPLO leads to limb function that is superior to that produced by extracapsular surgery. Firstly, Böddeker et al. (2012) concluded that the dogs treated with TPLO had faster recovery and improved limb function relative to the extracapsular capsular-fascial imbrication technique group 4 months after surgery. SIs for PVFs were 5.83% in the TPLO group and 19.05% in the extracapsular group 4 months postoperatively, although the difference was not statistically significant. Secondly, SIs for PVF and VI at trot were significantly more symmetrical for the TPLO group than for the extracapsular
group at all evaluation points (2 weeks, 8 weeks, 6 months, 12 months) postoperatively (Nelson et al. 2013). Thirdly, Gordon-Evans et al. (2013) evaluated ground reaction forces at walk and trot in a well-designed study 6 and 12 months after surgery in 40 dogs treated with the extracapsular fabellotibial suture technique and in 40 TPLO dogs. After 12 months, PVFs in affected limbs were 6% higher at walk and 11% higher at trot for dogs in the TPLO group relative to those in the extracapsular group; these differences were statistically significant.

In summary, TPLO seems to result in outcomes that are better than extracapsular repair and similar to extracapsular repair in approximately equal numbers of studies. Either the true differences between the techniques are too small to show significance in all studies or the difference in factors related to patients, surgical techniques, postoperative treatments, or evaluation methods cause variance in results. The available research is insufficient to allow conclusions to be drawn about the surgical outcome after intracapsular repair or TTA surgery in relation to other techniques.

**Alternatives to basic force plate analysis**

Force plate analysis has the disadvantage of measuring the dynamic weight bearing of only one limb at a time. In addition, force plate analysis is unable to evaluate swing phase of the stride and successive strides cannot be measured with a single force plate. As an alternative to basic force plate analysis, pressure sensitive walkways measuring several footsteps during one trial, equipment with force plates in series, and force plate treadmills have been developed and used also for evaluation of CCL-deficient dogs, as mentioned above (Au et al. 2010, Böddeker et al. 2012, Krotscheck et al. 2014). In addition to force plate analysis, the use of kinematic evaluation of gait in CCL disease has increased (Marsolais et al. 2003, Tashman et al. 2004, Lee et al. 2007, Sanchez-Bustinduy et al. 2010, deMedeiros et al. 2011). Kinematic analysis allows assessment of the whole stride cycle, evaluation of flexion and extension movements of joints and temporal and distance variables of the dog's gait (McLaughlin 2001). When kinematic analysis was used to evaluate changes related to CCL disease, CCL-deficient limbs were shown to have significantly lower stride length and paw velocity than healthy limbs (Sanchez-Bustinduy et al. 2010). After TPLO surgery, the stride length returned to normal by 12 weeks, but paw velocity remained lower than recorded in normal dogs (de Medeiros et al. 2011).

In kinetic and kinematic evaluation, the focus is on assessment of dynamic weight bearing and movement of the dog. Static weight bearing (SWB) that is measured while the dog is standing, has been evaluated in healthy dogs and also used in assessment of orthopedic outcome and perioperative pain (Horstman et al. 2004, Lascelles et al. 2006, Phelps et al. 2007, Lascelles et al. 2010, Davila et al. 2013). However, according to my knowledge the SWB has not been used to evaluate surgical outcome after CCL repair.

**2.6.4 Diagnostic imaging**

Radiographic evaluation of OA changes in stifle joints has across the years been a basic part of the outcome assessment after CCL surgery. Varying scales from a simple 4-grade classification (deRooster and vanBree 1999) to complex scoring systems (Elkins et al. 1991, Vasseur and Berry 1992, Innes et al. 2004) have been used. Although the OA changes provide evidence of pathology in the joint, the degree of these changes has been shown to correlate poorly with clinical function.
of the limb, and this must be taken into account in assessment of clinical outcome (Gordon et al. 2003). Postoperative radiography can also be used to evaluate certain complications of CCL surgery such as postoperative patellar tendonitis and tibial fractures (Kergosien et al. 2004, Carey et al. 2005, Pettitt et al. 2014).

Although one of the aims of CCL surgery has been to decelerate or halt the progression of degenerative joint disease, OA changes have been shown to advance after repair with both intracapsular and extracapsular techniques (Elkins et al. 1991, Vasseur and Berry 1992, Innes et al. 2004, Au et al. 2010). The newer dynamic stabilization techniques were first proposed to resolve these problems and stop the progression of OA (Slocum and Devine Slocum 1998), but later studies have proven that degenerative changes progress in most dogs also after surgery with osteotomy techniques (Rayward et al. 2004, Jerram et al. 2005, Lineberger et al. 2005, Hoffmann et al. 2006, Boyd et al. 2007, Hurley et al. 2007, Au et al. 2010, Morgan et al. 2010).

Of other diagnostic imaging modalities, MRI was reported to be more sensitive than radiography in assessing onset and progression of osteophytosis after experimental transection of CCL (D’Anjou et al. 2008). However, neither MRI nor computed tomography (CT) has been used to evaluate surgical outcome after CCL repair in clinical patients. Ultrasonographic examination has been used to evaluate postoperative signs of patellar ligament tendonitis after TTA and TPLO procedures (Mattern et al. 2006, Kühn et al. 2011, Pettitt et al. 2014).
The primary goal of this study was to evaluate the long-term (>1 year) surgical outcome after CCL repair in dogs. The secondary goal was to compare surgical techniques used to repair CCL rupture.

Specific aims of the study were as follows:

1. To report and compare normal reference data from force plate analysis in clinically healthy Rottweilers and Labrador Retrievers.

2. To describe a new method for measuring static weight bearing in pelvic limbs and to report the normal variance for the difference of weight bearing between pelvic limbs in clinically healthy Rottweilers and Labrador Retrievers.

3. To use an owner evaluation, including the validated Helsinki Chronic Pain Index, to assess chronic pain and long-term outcome after CCL surgery.

4. To use orthopedic, physiotherapeutic, radiographic, and force plate examinations for evaluation of long-term surgical outcome and function of the surgically treated limb after CCL surgery.
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4.1 Animals

4.1.1 Control dogs (I, III, IV)
Clinically healthy adult Rottweilers and Labrador Retrievers, voluntarily presented by their owners, were used for force plate evaluation in Study I, for measuring pelvic limb static weight bearing in Study III, and as a control population (control group) for force plate and physiotherapeutic examination in Study IV. The inclusion criteria were age 1-8 years, no known orthopedic problems or abnormal findings in orthopedic examination, and radiographic screening results free of elbow and hip dysplasia according to the Fédération Cynologique Internationale screening protocol (grade 0/0 for elbow dysplasia and grade A or B for hip dysplasia).

4.1.2 Surgically treated dogs (II, IV)
The case selection for Study II was done in cooperation with the Veterinary Teaching Hospital of the University of Helsinki and 5 private orthopedic referral clinics in Finland (Espoon eläinsairaala, Finnin Ratsutila ja Eläinlääkintä, HauMau, Malmin eläinklinikka Apex and Mevet). Privately owned dogs with CCL rupture that had been surgically treated with intracapsular, extracapsular, TPLO, or TTA technique between January 2004 and December 2006 were included. Patients with other known concomitant stifle problems, such as patellar luxation, collateral ligament damage, and septic or immune-mediated arthritis, at the time of the initial CCL surgery were excluded.

Based on the results of Study II and another questionnaire study (unpublished data evaluating the outcome of TTO technique), owners were invited to bring their dogs for a clinical evaluation (study group in Study IV). The inclusion criteria were surgically treated unilateral CCL rupture, a minimum follow-up time interval of 1.5 years between surgery and evaluation, and a body weight >17 kg. In addition to exclusion criteria set for Study II, also dogs with bilaterally treated CCL rupture or other known orthopedic or neurologic problems were excluded. Any NSAID, opioid, or corticosteroid pain medications and nutraceutical and fatty acid supplements were withdrawn at a minimum of 7 days, long-term corticosteroids 30 days, and pentosan polysulfate 90 days before the evaluation.

In Studies I and II, institutional guidelines for research on animals were followed, and Studies III and IV were approved by the Ethics Committee of Viikki campus, University of Helsinki. In addition, a written consent was obtained from all owners.

4.2 Medical records (II, IV)
With permission from the owners, the medical records of the surgically treated dogs were reviewed to determine the surgical date, technique used, surgically treated limb, information about meniscal tear, and possible complications or revision surgery needed.
4.3 Owner evaluation and Helsinki Chronic Pain Index (II)

A questionnaire was sent to the owners of surgically treated dogs that fulfilled the inclusion criteria for the study. In addition to signalment, CCL surgery information, including the time of the operation/operations and the type of the rupture (uni- or bilateral), the duration of the clinical signs before surgery (< 1 month, 1 to < 2 months, 2 to < 3 months, 3 – 4 months, > 4 months), and the duration of postoperative lameness (< 1 month, 1 to < 2 months, 2 to < 3 months, 3 – 6 months, > 6 months, or dog is still lame), was collected. If the dog was bilaterally surgically treated, the owner was asked to answer based on the cruciate surgery performed between 2004 and 2006, and if both stifle joints underwent surgery during this period, based on the latter surgery. Owners were also asked whether the dog had received postoperative physiotherapy.

The Helsinki Chronic Pain Index (HCPI) was used to evaluate possible signs of chronic pain at follow-up (time interval between surgery and the questionnaire). It contained 11 questions on the dog's mood, lameness, and willingness to move, play, and jump. Owners were asked to select the answer that best described their dog on a 5-point descriptive scale. The answers were later tied to a value (0 to 4), which when summed yielded a total index minimum score of 0 and a maximum score of 44 (Hielm-Björkman et al. 2003, Hielm-Björkman et al. 2009).

Owners were also asked to give their opinion on the surgical outcome (excellent, good, fair, or poor), and rate the frequency of lameness of the dog’s surgically treated limb (never, hardly ever, sometimes, often, or always) and the dog's willingness to bear weight equally on the surgically treated and contralateral limb (always, very often, often, sometimes, or hardly ever) at follow-up.

The questionnaire also inquired about the need for long-term administration of nonsteroidal anti-inflammatory drugs (NSAIDs, e.g. carprofen and meloxicam) as well as whether the drug was administered for the surgically treated stifle joint. Similar questions were asked about nutraceutical products (i.e. glucosamine and chondroitin sulfate).

4.4 Clinical evaluation (I,III,IV)

Clinical evaluation in healthy dogs consisted of physical, orthopedic, and physiotherapeutic examinations, anatomic measurements, and force plate analysis (Studies I, III, and IV) and in surgically treated dogs physical, orthopedic, radiographic, and physiotherapeutic examinations and force plate analysis (Study IV). During the evaluation of the surgically treated dogs the members of the research team were unaware of which hind limb had been operated on and the surgical technique used.

4.4.1 Orthopedic examination (I,IV)

An orthopedic examination included lameness evaluation on a scale from 0 to 4 (no lameness, mild lameness or minor gait abnormality, moderate lameness or gait abnormality, severe weight-bearing lameness, non-weight-bearing lameness) (Mostafa et al. 2009) and palpation of the thoracic and pelvic limbs and spine as well as evaluation of conscious proprioception and withdrawal reflex. The stifle joints were palpated for pain (no, mild, moderate, severe), crepitation (no, mild, moderate, severe), periarticular swelling (no, mild, moderate, severe) and decrease in ROM (no, mild, moderate, severe), and patellar luxation, evaluated with the tibial
compression test and in sedation with the cranial drawer test. The spine was evaluated for pain and all other joints for pain, crepitation, swelling, decreased ROM, and instability. While sedated, an Ortolani test was used to evaluate hip joint laxity.

4.4.2 Radiographic examination (IV)

The stifle, hip, and elbow joints bilaterally as well as the lumbar spine in surgically treated dogs were radiographed under sedation and evaluated. The amount of OA in stifle joints was evaluated from mediolateral and craniocaudal views on a scale from 0 to 3 (no, mild, moderate, severe) (deRooster and vanBree 1999). In addition, the amount of OA in the hip joints was evaluated from an extended ventrodorsal view, in the elbow joints from 45° flexed mediolateral and craniocaudal views, and in the lumbar spine from laterolateral and ventrodorsal views.

4.4.3 Anatomic measurements (I)

Anatomic measurements were performed in healthy control dogs in order to normalize ground reaction forces according to conformational data. With the dog in standing position, distances from the ground to the highest point of the scapula, to the highest point of the iliac crest, and to the highest point of the olecranon process, as well as the length of the spine from the spinous process of the 2nd thoracic vertebra to the end of the last lumbar vertebra were measured. Also, humeral length (distance from greater tubercle to lateral epicondyle) and femoral length (distance from greater trochanter to lateral epicondyle) were measured while the dog was in lateral recumbency. Measurements were read by a second person, taken 3 times using a metric scale, and averaged.

Functional limb length of a dog corresponding to the height of the center of the mass above the point of ground contact was calculated as a distance from the ground to the olecranon process plus one-third of the distance from the olecranon process to the highest point of the scapula (Bertram et al. 2000). Functional limb length and mean trotting velocity were used to calculate a dimensionless relative trotting velocity according to the equation

\[ V_{rel} = \frac{v}{(gh)^{1/2}} \]

where \( v \) is the mean trotting velocity, \( h \) is the functional limb length, and \( g \) is the gravitational acceleration (9.81 m/s²).

4.4.4 Force plate analysis (I,IV)

Ground reaction forces were measured using a piezoelectric force plate (Kistler force plate, type 9286, Kistler Instrumente AG, Winterthur, Switzerland) embedded in the center of a 14-m runway and a computer-based software program (Aquire 7.3, Sharon Software Inc., Dewitt, MI). Velocity and acceleration were measured by use of 3 photoelectric cells, positioned 1 m apart, and a start-interrupt timer system (Sharon Software Inc.). Dogs were guided over the force plate by the owner or a member of the research team at a trotting speed of 2.10-2.50 m/s and an acceleration of −0.5 to + 0.5 m/s². A trial was considered valid when the thoracic limb was followed by the ipsilateral pelvic limb, both fully contacting the plate, and with the dog trotting next to the handler without pulling on the leash. The trial was discarded if the dog was distracted during the measurement, if the limb struck the edge of the plate, or if any portion of the contralateral paw hit the plate. Two members of the research team evaluated the trial to
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confirm which feet touched the plate. After visual examination of the traces for consistency, a blinded assistant (person not otherwise participating in the study) chose 5 valid measurements for each side, and data from these trials were averaged.

Study I

Peak vertical and craniocaudal forces and associated impulses, stance time, time to peak vertical force, breaking time, propelling time, and mean rising and falling slopes in thoracic and pelvic limbs were evaluated in Labrador Retrievers and Rottweilers.

In the initial analysis and when the effects of relative velocity and anatomic measurements on force plate values were evaluated, the data of ground reaction forces and impulses normalized for the dog's body weight were used. When the effect of body weight on force plate values was evaluated, raw data un-normalized for body weight were used to prevent double normalization of the values.

Study IV

Peak vertical forces and vertical impulses in thoracic and pelvic limbs were evaluated as percentages of the dog's body weight. In addition, distribution percentages per limb of peak vertical forces (DPVF) were calculated for study group dogs using the equation

\[
\text{DPVF}_{\text{STPL}} = \frac{100 \, \text{PVF}_{\text{STPL}}}{(\text{PVF}_{\text{STPL}} + \text{PVF}_{\text{CPL}} + \text{PVF}_{\text{ITL}} + \text{PVF}_{\text{CTL}})},
\]

where \(\text{PVF}_{\text{STPL}}\) is the PVFs recorded in the surgically treated limbs, \(\text{PVF}_{\text{CPL}}\) in the contralateral pelvic limbs, \(\text{PVF}_{\text{ITL}}\) in the ipsilateral thoracic limbs, and \(\text{PVF}_{\text{CTL}}\) in the contralateral thoracic limbs. The DPVFs were calculated similarly for contralateral pelvic limbs of study group dogs and for pelvic limbs of control group dogs.

The symmetry index (SI) (Herzog et al. 1989) was calculated for the pelvic limb PVF and VI in surgically treated (study group) and control dogs using the equation

\[
\text{SI} = \frac{200(\text{X}_{\text{CPL/L}} - \text{X}_{\text{STPL/R}})}{(\text{X}_{\text{CPL/L}} + \text{X}_{\text{STPL/R}})},
\]

where \(\text{X}_{\text{CPL/L}}\) is the value recorded in the contralateral (study group) or left (control group) pelvic limb and \(\text{X}_{\text{STPL/R}}\) is the value recorded in the surgically treated (study group) or right (control group) pelvic limb. In surgically treated dogs, an SI value of 0 indicates perfect symmetry, a positive value decreased dynamic weight bearing in the surgically treated limb, and a negative value decreased dynamic weight bearing in the contralateral pelvic limb. The SIs were calculated similarly for control group dogs, but absolute values of the SIs were used. Thus, only the magnitude of SI was evaluated, and side (right or left pelvic limb) of deviation from perfect symmetry was disregarded.

4.4.5 Physiotherapeutic examination (III, IV)

A physiotherapeutic examination was done by a physiotherapist specialized in veterinary physiotherapy and consisted of 14 tests, as described previously (Hyytiäinen et al. 2013). In Study III, the use of bathroom scales in measuring SWB was described, and normal variance of the quantitatively measured static weight bearing (qmSWB) was reported. In Study IV, of all 14 tests, results of the visual evaluation of functional active range of motion (AROM), symmetry of
thrust between pelvic limbs, evaluation of muscle atrophy, qmSWB, and passive range of motion (PROM) in stifl e joints were presented in surgically treated dogs.

**Static weight bearing (III, IV)**

Quantitative measurement of SWB in the pelvic limbs was done using two identical digital bathroom scales (Medica plus M-135, Truebell Vantaa, Finland), with the thoracic limbs placed on a custom-made platform of the same height as the scales. The measurement accuracy of the scale was 0.1 kg, with measurement range from 3 kg to 150 kg. The owner was instructed to hold the dog from the front, keeping it in a straight square-standing position and not to provide any manual support for the dog. The examiner kneeled behind the dog, placed the pelvic limbs symmetrically onto the scales and recorded measurements for both limbs.

The results of four measurements on each limb were averaged and converted from kilograms to percentages proportional to the body weight (SWB%) and evaluated as mean ± SD values. In addition, difference in SWB between the pelvic limbs (DiffSWB%) was calculated using the following equation

\[
\text{DiffSWB\%} = 100 \left( \frac{\text{SWB}_{\text{CPL/L}} (\text{kg}) - \text{SWB}_{\text{STPL/R}} (\text{kg})}{\text{body weight (kg)}} \right)
\]

where SWB\text{CPL/L} is the value recorded in the contralateral (study group) or left (control group) pelvic limb and SWB\text{STPL/R} is the value recorded in the surgically treated (study group) or right (control group) pelvic limb. In surgically treated dogs, a DiffSWB\% value of 0 indicates perfect symmetry, a positive value smaller SWB in the surgically treated pelvic limb, and a negative value smaller SWB in the contralateral pelvic limb. The absolute value of the DiffSWB\% was used in the control group, and thus, the difference between right and left hind limb weight bearing was disregarded.

**Active range of motion and thrust (IV)**

The dog was led over a 20-m distance and asked to "sit and sit-to-move", and similarly "lie down and lie-to-move" 3 times. The position of pelvic limbs during sitting and lying was observed, and possible functional limitations or compensation of the pelvic limbs in sitting or lying position, such as external rotation or abduction of the limb, limited flexion of stifl e or tarsal joints, or weakness/asymmetry of pelvic limbs in thrust from the ground, were noted.

**Muscle atrophy (IV)**

The symmetry of the muscle bulk in pelvic limbs was evaluated manually by palpating and comparing simultaneously the width of the thigh muscles.

**Passive range of motion (IV)**

The passive range of motion in the stifl e joints was measured from unsedated dogs in lateral recumbency using a flexible 180° universal goniometer with a 5° scale. Three measurements of each joint in maximal flexion and extension from both pelvic limbs were taken and averaged. In addition to reporting the mean ± SD values, the PROM measurements were also evaluated as percentages of the contralateral limbs. Because flexion angles were lower (higher in number) in
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the surgically treated limbs, for calculation of percentages the flexion angles were transformed by subtracting the angle from 180°.

4.5 Statistical analyses

Data analyses were performed with statistical software programs. SPSS version 15.0 for Windows (SPSS Inc., Chigaco, IL) and SAS system version 9.1 (SAS Institute Inc., Cary, NC) were used in Study I, PASW version 18.0 for Windows (SPSS Inc., Chigaco, IL) and SAS system version 9.1 in Study II, SAS system version 9.2 in Study III, and SPSS version 21 for Windows in Study IV. Statistical significance was set at the 5% level in all studies. Kolmogorov-Smirnov and Shapiro-Wilk tests served to determine whether data were normally distributed.

4.5.1 Study I

The results were summarized as mean ± SD. Differences between left and right thoracic and left and right pelvic limbs were tested with the Wilcoxon rank test, and right and left limb values were combined. Pearson's or Spearman's correlation tests were used to analyze the relationship between weight and force plate values. Independent samples t-test or Mann-Whitney rank-sum test were used to detect differences in ground reaction forces between breeds. Linear regression analysis was applied to evaluate the effect of body weight and anatomic measurements on force platform values. Logarithmic transformations \( x' = \log(x+100) \) were first conducted to normalize the distribution of the variables. The effect of dog breed on force plate values was tested by ANCOVA, which allowed the removal of variance arising from relative velocity, anatomic measurements, and body weight of the dog.

4.5.2 Study II

Explanatory variables included age, body weight, duration of clinical signs before surgery, surgical technique (intracapsular, extracapsular, or osteotomy), unilateral or bilateral surgery, meniscal integrity (damaged vs. intact), number of surgical procedures (1 vs. ≥ 2), and follow-up time, and outcome variables included HCPI, surgical outcome (excellent, good, fair, poor), duration of postoperative lameness, frequency of lameness at follow-up, and willingness to bear weight equally on the surgically treated and contralateral limbs at follow-up. Results from nominal and ordinal data were reported as frequencies and percentages. For continuous data, the results were summarized as mean ± SD and for HCPI, also as 95% confidence interval. The Spearman rank test served to analyze the association between the HCPI and continuous or ordinal explanatory variables as well as other outcome variables. An unpaired t-test was used to compare differences in HCPI and age between the excellent and good outcome groups as well as between dogs with and without meniscal tears. The Mann-Whitney rank-sum and unpaired t-tests served to compare differences in explanatory and outcome variables between the dogs that underwent surgery at least twice and dogs that underwent surgery only once. The Kruskall-Wallis statistic and the Bonferroni-Holm correction method were used to compare differences for ordinal outcome variables between surgical techniques. An ANOVA and Bonferroni and Tukey post hoc analyses were used to compare differences for continuous variables between the surgical techniques. For comparison of HCPI between surgical techniques, ANCOVA allowed removal of the variance arising from the age of the dog.
4.5.3 Study III

Based on calculated mean ± SD difference in static weight bearing between the pelvic limbs in healthy control dogs, a cut-off value for normal DiffSWB% was determined (mean + SD). An unpaired t-test was used to compare differences in SWB% and DiffSWB% between the Rottweiler and Labrador breeds.

4.5.4 Study IV

Results from nominal and ordinal data (surgical technique, condition of the meniscus, stifel joint palpation and radiographic findings, AROM, muscle atrophy), SI, and DiffSWB% were reported as frequencies and percentages. For continuous data (age at time of surgery, body weight at time of evaluation, follow-up, force plate data, SWB%, PROM) the results were summarized as mean ± SD.

Other concurrent orthopedic problems were known to have a potential influence on results of ground reaction forces, AROM, SWB and muscle atrophy. In these evaluations the results were analyzed separately in dogs that, based on orthopedic and radiographic examinations, did not have concurrent orthopedic problems (subgroup 1). When PROMs of surgically treated limbs were compared with contralateral limbs, the results were analyzed in dogs that did not have concurrent contralateral stifel or tarsal joint problems (subgroup 2). Concurrent problems in other joints, such as hip dysplasia or elbow OA were allowed, because these findings were regarded to have no influence on results of PROM in stifel or tarsal joints.

When SIs were analyzed, the control group was used to determine the cut-off value for differentiation between normal and lame dogs by using mean + SD. Based on the cut-off values, the surgically treated dogs were assigned to be lame on the surgically treated limb, to have normal gait symmetry, or to be lame on the contralateral pelvic limb. Similarly, when DiffSWB% were evaluated, the cut-off value determined in Study III was used to classify the surgically treated dogs to have symmetrical qmSWB, decreased qmSWB on the surgically treated limb, or decreased qmSWB on the contralateral pelvic limb.

The Kruskall-Wallis statistic with pairwise comparisons was used to evaluate differences in age, follow-up, stifel joint palpation findings, and amount of radiographic OA between surgical techniques, and unpaired t-test or ANOVA was used to evaluate differences in body weight between study group and control group dogs or surgical techniques. The Mann-Whitney rank-sum test for not normally distributed and unpaired t-test for normally distributed force plate, SWB%, and PROM data were used to evaluate differences between surgically treated and contralateral limbs or control dog limbs. Similarly, the Kruskall-Wallis test with pairwise comparisons for not normally distributed and ANOVA with Bonferroni and Tukey post hoc analyses for normally distributed force plate, SWB%, and PROM data were used to evaluate differences between surgical techniques.
5 Results

5.1 Animals

5.1.1 Control dogs (I, III, IV)

A group of 9 Rottweilers and 12 Labrador Retrievers was used (Table 1). Rottweilers were significantly heavier (43.6 ± 5.6 kg) than Labrador Retrievers (29.4 ± 2.8 kg) (P < 0.001). No significant difference in age was present between the breeds.

5.1.2 Surgically treated dogs (II, IV)

During the study period, 507 dogs were surgically treated. Owners of 272 dogs (53.6%) answered the questionnaire, and of returned questionnaires, 253 were eligible for evaluation in Study II (Table 1). The most common breeds were Labrador Retriever (14.2%), mixed breed (9.9%), Rottweiler (8.3%), Bichon Frisé (6.3%), German Shepherd Dog (3.2%), Golden Retriever (2.8%), Newfoundland Dog (2.8%), Bernese Mountain Dog (2.4%), and Staffordshire Bull Terrier (2.4%).

A modification of the original intracapsular technique (Arnozcky et al. 1979) was used in 34.8% of dogs, two variations of an original modification of the extracapsular technique (Flo 1975) with a nylon leader line or polyester sutures in 34.4% of dogs, and osteotomy techniques in 24.9% of dogs, including TPLOs (13.4%) and TTAs (11.5%), both performed as described elsewhere (Slocum and Devine Slocum 1993, Lafaver et al. 2007) (Table 1). In addition, in 5.9% of dogs the limb underwent surgery ≥ 2 times with a single or multiple techniques. The diagnosis was confirmed and the joint visually inspected via arthrotomy in all included dogs. The condition of the meniscus was reported for 126 dogs (49.8%), with damage in 42% and an intact meniscus in 58%.

A significant difference was found in body weight between dogs that underwent surgery via the different techniques (P < 0.001). The dogs in the extracapsular group were older at the time of surgery and at the time of evaluation than the dogs in the intracapsular and osteotomy groups (P < 0.005). In addition, the follow-up time was shorter in the osteotomy group than in the extracapsular and intracapsular groups (P < 0.001).


Table 1 Description of the evaluated animals.

<table>
<thead>
<tr>
<th></th>
<th>Surgically treated dogs</th>
<th>Control dogs (I,III,IV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All</td>
<td>Int</td>
</tr>
<tr>
<td>Number of dogs</td>
<td>253</td>
<td>87</td>
</tr>
<tr>
<td>(220)</td>
<td></td>
<td>(72)</td>
</tr>
<tr>
<td>Age at time of surgery (years)</td>
<td>5.9 ± 3.3</td>
<td>5.8 ± 3.0</td>
</tr>
<tr>
<td>Weight at follow-up (kg)</td>
<td>30.0 ± 17.9</td>
<td>31.4 ± 16.7</td>
</tr>
<tr>
<td>Follow-up (years)</td>
<td>2.7 ± 0.8</td>
<td>2.9 ± 0.8</td>
</tr>
</tbody>
</table>

Age at time of surgery and at time of evaluation, body weight, and follow-up of the dogs are reported as mean ± SD. () number of dogs alive at time of evaluation. Int, intracapsular; Ext, extracapsular; Ost, osteotomy.

For clinical evaluation in Study IV, 47 study group dogs were assessed (Table 1). The breeds were Labrador Retriever (15), Rottweiler (6), mixed breed (4), Golden Retriever (3), Bernese Mountain Dog (2), Doberman (2), Newfoundland Dog (2), Nova Scotia Duck Tolling Retriever (2), and one each of Beauceron, Black Russian Terrier, Bordeaux Dog, Bullmastiff, Collie, Dalmatian, Giant Schnauzer, Karelian Bear Dog, Short-Haired German Pointer, South African Boerboel, and Wheaten Terrier. An intracapsular technique was used in 19 of these dogs (40.4%), an extracapsular technique in 7 dogs (14.9%), and an osteotomy technique, including 9 TPLOs, 7 TTA’s, and 5 TTOs, performed as described in Bruce et al. (2007), in 21 dogs (44.7%). The condition of the meniscus was reported for 23 dogs (48.9%), with damage in 10 and an intact meniscus in 13 dogs. In contrast to Study II, there was no significant difference in age or body weight of the dogs between the surgical technique groups. The mean follow-up was, however, significantly shorter in the osteotomy group than in the intracapsular or extracapsular groups (P < 0.005) (Table 1).

The dogs in the study group were significantly older than the healthy control dogs (P < 0.001). No significant difference was found in body weight between the study group and healthy control group dogs.

5.2 Owner evaluation and Helsinki Chronic Pain Index (II)

Owner assessment of duration of postoperative lameness was < 3 months for most dogs (77.9%). Postoperative rehabilitation administered by a physiotherapist was used in 15.3% of dogs. Owners reported the surgical outcome in 226 dogs and felt it was excellent in 54%, good in 42.9%, fair
Results

in 0%, and poor in 3.1%. Owners’ long-term assessments of lameness and weight bearing of the surgically treated limb are reported in Table 2. Of 213 and 196 dogs, 12.2% were receiving NSAIDs and 25.0% nutraceuticals (i.e. glucosamine and chondroitin sulfate), respectively, for the surgically treated stifl e joint.

Table 2 Owners' long-term assessment of lameness and weight bearing of the surgically treated limb.

<table>
<thead>
<tr>
<th>Lameness (n=215)</th>
<th>Owner assessment of lameness of surgically treated limb at follow-up</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Never</td>
</tr>
<tr>
<td>Lameness</td>
<td>45.1% (97)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Owner assessment of weight bearing at follow-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Always</td>
</tr>
<tr>
<td>Willingness to bear weight equally on treated and contralateral limb (n=212)</td>
</tr>
</tbody>
</table>

Results expressed as percentage (number) of dogs.

The HCPI (mean ± SD, 8.9 ± 6.3; range, 0 to 24) could be calculated for 206 dogs, and 31.1% of these had an HCPI ≥ 12. Dogs that either had died, had recently undergone surgery on the contralateral stifl e joint, or had missing answers to HCPI questions were excluded from HCPI determination. The dog’s age at the time of the questionnaire and HCPI were positively associated (r = 0.252; P < 0.001). The HCPI in dogs with good outcomes (11.8 ± 5.4; 95% CI, 10.6 to 12.9) was significantly (P<0.001) higher than in dogs with excellent outcomes (6.1 ± 5.7; 95% CI, 5.1 to 7.2) (Figure 7). However, no significant difference in age was found between surgical outcome groups. The body weight of the dog, duration of clinical signs before surgery, follow-up time, and presence or absence of a meniscal tear had no significant association with the HCPI. The duration of postoperative lameness and HCPI were positively correlated (r = 0.210; P = 0.002).
In 15 dogs, the cruciate ligament-deficient limb underwent surgery more than once. In these dogs, the duration of postoperative lameness was significantly (P = 0.018) longer, and willingness to bear weight equally on the surgically treated and contralateral limb at follow-up was significantly (P = 0.009) lower than in dogs that underwent surgery only once. Signalment or other outcome variables did not differ significantly between dogs that underwent surgery more than once and dogs that underwent surgery only once.

When surgical outcome was compared with the surgical techniques used, the dogs that underwent surgery with ≥ 2 techniques on the same stifle joint were excluded (n=11). The owner’s assessment of duration of postoperative lameness in dogs treated with osteotomy techniques was significantly (P = 0.014; Bonferroni-Holm test significance at P < 0.016) shorter than in dogs treated with the intracapsular technique (Figure 8). No significant difference was found between surgical techniques in frequency of lameness or willingness to bear weight on the surgically treated limb at follow-up (Figures 9 and 10). The HCPI in dogs treated with osteotomy techniques was significantly (P = 0.030) lower than in dogs treated with the extracapsular technique. However, after the difference in age between the dogs in the osteotomy and extracapsular groups was controlled with an ANCOVA, no significant difference in HCPI between these dogs was found. Apart from a positive association between the dog’s age and HCPI, there was no association between signalment variables or follow-up time and the outcome variables used to compare surgical techniques.
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Figure 8 Composite bar graph of owner assessment of length of postoperative lameness in the surgically treated limb (percentage) after treatment with intracapsular (n=87), extracapsular (n=88), and osteotomy (n=61) techniques.

Figure 9 Composite bar graph of owner assessment of frequency of lameness in the surgically treated limb (percentage) at follow-up after treatment with intracapsular (n=78), extracapsular (n=70), and osteotomy (n=56) techniques.
Figure 10 Composite bar graph of owner assessment of willingness to bear weight equally on the surgically treated and contralateral limb (percentage) at follow-up after treatment with intracapsular (n=77), extracapsular (n=70), and osteotomy (n=54) techniques.

5.3 Clinical evaluation (I,III,IV)

5.3.1 Orthopedic and radiographic examination (I, IV)

The 21 healthy control dogs did not show any signs of orthopedic disease or lameness. Of surgically treated dogs, grade 1/4 lameness of the surgically treated limb was seen in 8 dogs (3 intracapsular, 1 extracapsular, 4 osteotomy). One dog treated with the intracapsular technique had grade 2/4 lameness. The gait could not be evaluated in one dog. Orthopedic and radiographic findings in the surgically treated stifle joints are presented in Table 3. No significant differences were found between surgical techniques in pain response to stifle flexion/extension. The amount of stifle joint crepitation was significantly lower in the osteotomy group than in the extracapsular (P = 0.030) or intracapsular (P = 0.028) groups, and the amount of periarticular swelling was significantly lower in the osteotomy group than in the extracapsular group (P = 0.047). The drawer sign was tested in 39 dogs. Of 12 dogs that presented a positive drawer sign, 5 had been treated with intracapsular and 7 with osteotomy techniques. The tibial compression test was negative in all stifle joints. The severity of radiographic OA was lower in the osteotomy group than in the intracapsular group (P = 0.013). Based on orthopedic and radiographic examinations, 21 surgically treated dogs were included in subgroup 1 and 33 dogs in subgroup 2.
5.3.2 Anatomic measurements (I)

Anatomic measurements were available for 20 healthy control dogs. Mean ± SD distance from the ground to the highest point of the scapular spine and the highest point of the iliac crest for Rottweilers were 0.610 ± 0.036 and 0.607 ± 0.033 m and for Labrador Retrievers 0.537 ± 0.034 and 0.536 ± 0.030 m, respectively. Mean ± SD humeral length and femoral length for Rottweilers were 0.192 ± 0.011 and 0.195 ± 0.013 m and for Labrador Retrievers 0.173 ± 0.013 and 0.172 ± 0.016 m, respectively. Mean ± SD length of the spine for Rottweilers was 0.468 ± 0.021 m and for Labrador Retrievers 0.396 ± 0.343 m. Functional limb length for Rottweilers was 0.433 ± 0.026 m and for Labrador Retrievers 0.377 ± 0.025 m. All anatomic measurements were significantly larger in Rottweilers (P<0.001).

5.3.3 Force plate analysis (I,IV)

Study I

Initial force plate data and differences between the Rottweilers and Labrador Retrievers are presented in Table 4. Mean ± SD values for velocity and acceleration were 2.28 ± 0.05 m/s and 0.02 ± 0.14 m/s² for Rottweilers and 2.25 ± 0.05 m/s and -0.09 ± 0.12 m/s² for Labrador Retrievers, respectively. No significant difference existed between breeds in trotting velocity (P=0.055) but there was a significant difference between breeds in acceleration (P = 0.013).

When breeds were combined, body weight correlated with all force platform values that were different between breeds. Based on the anatomic measurements, calculated relative velocities in Rottweilers and Labrador Retrievers were 1.11 ± 0.04 and 1.17 ± 0.04, respectively, with significant difference between breeds (P<0.001).

When anatomic variables were analyzed, functional limb length was found to have the most significant effect on force plate values and was chosen to be used in the ANCOVA as the anatomic variable. ANCOVA was applied to evaluate differences in force plate values between breeds when the effect of relative velocity and functional limb length, separately and together,

### Table 4

<table>
<thead>
<tr>
<th>Severity of stifle joint finding</th>
<th>No findings</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain response to stifle flexion/extension (n=47)</td>
<td>68.1% (32)</td>
<td>25.5% (12)</td>
<td>6.4% (3)</td>
<td>-</td>
</tr>
<tr>
<td>Periarticular swelling (n=47)</td>
<td>-</td>
<td>36.2% (17)</td>
<td>53.2% (25)</td>
<td>10.6% (5)</td>
</tr>
<tr>
<td>Crepitation (n=47)</td>
<td>6.4% (3)</td>
<td>34.0% (16)</td>
<td>51.1% (24)</td>
<td>8.5% (4)</td>
</tr>
<tr>
<td>Cranial drawer sign (n=39)</td>
<td>69.2% (27)</td>
<td>15.4% (6)</td>
<td>12.8% (5)</td>
<td>2.6% (1)</td>
</tr>
<tr>
<td>Radiographic OA (n=46)</td>
<td>2.2% (1)</td>
<td>19.6% (9)</td>
<td>45.6% (21)</td>
<td>32.6% (15)</td>
</tr>
</tbody>
</table>

Results are expressed as percentages (number) of dogs. n, number of dogs evaluated.
was eliminated from initial force plate data (Table 5). When the variation arising from relative velocity, functional limb length, or both was removed, differences between breeds in thoracic limb peak vertical forces as well as rising and falling slopes and in pelvic limb vertical impulses remained, but were eliminated in thoracic limb vertical impulses. For craniocaudal forces and impulses, the results were inconsistent. Finally, when ANCOVA was used to remove the effect of body weight from raw force plate data, all differences between the breeds were eliminated.

Table 4 Initial force plate data of healthy Rottweilers and Labradors

<table>
<thead>
<tr>
<th>Gait variable</th>
<th>Limb</th>
<th>Rottweilers (100*N/N)</th>
<th>Labradors (100*N/N)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stance time (ms)</td>
<td>TL</td>
<td>274.9 ± 17.1</td>
<td>234.3 ± 11.5</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>238.1 ± 16.4</td>
<td>212.6 ± 15.5</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>PVF (100*N/N)</td>
<td>TL</td>
<td>117.0 ± 6.1</td>
<td>125.3 ± 10.7*</td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>71.9 ± 2.8</td>
<td>72.5 ± 4.8</td>
<td>0.657</td>
</tr>
<tr>
<td>VI (100*N-s/N)</td>
<td>TL</td>
<td>17.1 ± 1.3</td>
<td>15.7 ± 0.8</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>9.3 ± 0.6</td>
<td>8.3 ± 0.6</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>PVF time (ms)</td>
<td>TL</td>
<td>131.3 ± 9.3</td>
<td>116.1 ± 7.6</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>102.0 ± 6.8</td>
<td>92.2 ± 8.1</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>AvRS (100*N/N/ms)</td>
<td>TL</td>
<td>0.90 ± 0.09</td>
<td>1.08 ± 0.16*</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>0.71 ± 0.06</td>
<td>0.78 ± 0.11</td>
<td>0.009</td>
</tr>
<tr>
<td>AvFS (100*N/N/ms)</td>
<td>TL</td>
<td>-0.82 ± 0.06</td>
<td>-1.05 ± 0.12</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>-0.54 ± 0.06</td>
<td>-0.60 ± 0.08</td>
<td>0.006</td>
</tr>
<tr>
<td>Break peak (100*N/N)</td>
<td>TL</td>
<td>-16.5 ± 2.6</td>
<td>-18.2 ± 2.6*</td>
<td>0.034</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>-6.6 ± 2.3</td>
<td>-6.3 ± 1.7</td>
<td>0.583</td>
</tr>
<tr>
<td>Break imp (100*N-s/N)</td>
<td>TL</td>
<td>-1.50 ± 0.30</td>
<td>-1.43 ± 0.19</td>
<td>0.341</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>-0.27 ± 0.13</td>
<td>-0.25 ± 0.11</td>
<td>0.712</td>
</tr>
<tr>
<td>Break time (ms)</td>
<td>TL</td>
<td>79.5 ± 9.8</td>
<td>76.5 ± 9.9</td>
<td>0.477</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>27.5 ± 5.5</td>
<td>27.7 ± 8.8</td>
<td>0.611</td>
</tr>
<tr>
<td>Prop peak (100*N/N)</td>
<td>TL</td>
<td>8.3 ± 1.4</td>
<td>9.5 ± 1.5</td>
<td>0.007</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>10.8 ± 1.9</td>
<td>11.3 ± 1.5</td>
<td>0.384</td>
</tr>
<tr>
<td>Prop imp (100*N-s/N)</td>
<td>TL</td>
<td>0.62 ± 0.10</td>
<td>0.59 ± 0.11</td>
<td>0.366</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>0.87 ± 0.17</td>
<td>0.81 ± 0.16</td>
<td>0.277</td>
</tr>
<tr>
<td>Prop time (ms)</td>
<td>TL</td>
<td>204.1 ± 18.6</td>
<td>177.7 ± 9.0</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>149.2 ± 8.7</td>
<td>134.6 ± 9.9</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

*Significant (P<0.05) difference present between right and left limb values. Forces, impulses, and slopes are reported as percentages of body weight. PVF, peak vertical force; VI, vertical impulse; PVF time, time to peak vertical force; AvRS, average vertical rising slope; AvFS, average vertical falling slope; Break peak, breaking peak force; Break imp, breaking impulse; Break time, breaking time; Prop peak, propelling peak force; Prop imp, propelling impulse; Prop time, propelling time; TL, thoracic limb; PL, pelvic limb.
Table 5 Differences between Rottweilers and Labradors in force plate data before and after analyses of covariance.

<table>
<thead>
<tr>
<th>Gait variable</th>
<th>Limb</th>
<th>Initial data</th>
<th>Vrel</th>
<th>Funct</th>
<th>Vrel + Funct</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stance time</td>
<td>TL</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.592</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>&lt;0.001</td>
<td>0.001</td>
<td>0.008</td>
<td>0.007</td>
<td>0.186</td>
</tr>
<tr>
<td>PVF</td>
<td>TL</td>
<td>0.003</td>
<td>0.012</td>
<td>0.003</td>
<td>0.002</td>
<td>0.492</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>0.657</td>
<td>0.477</td>
<td>0.422</td>
<td>0.494</td>
<td>0.387</td>
</tr>
<tr>
<td>VI</td>
<td>TL</td>
<td>&lt;0.001</td>
<td>0.051</td>
<td>0.548</td>
<td>0.497</td>
<td>0.833</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>&lt;0.001</td>
<td>0.002</td>
<td>0.001</td>
<td>0.001</td>
<td>0.812</td>
</tr>
<tr>
<td>PVF time</td>
<td>TL</td>
<td>&lt;0.001</td>
<td>0.001</td>
<td>0.009</td>
<td>0.006</td>
<td>0.358</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>&lt;0.001</td>
<td>0.023</td>
<td>0.074</td>
<td>0.050</td>
<td>0.690</td>
</tr>
<tr>
<td>AvRS</td>
<td>TL</td>
<td>&lt;0.001</td>
<td>0.004</td>
<td>0.004</td>
<td>0.003</td>
<td>0.371</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>0.009</td>
<td>0.248</td>
<td>0.417</td>
<td>0.337</td>
<td>0.955</td>
</tr>
<tr>
<td>AvFS</td>
<td>TL</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.482</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>0.006</td>
<td>0.088</td>
<td>0.162</td>
<td>0.151</td>
<td>0.053</td>
</tr>
<tr>
<td>Break peak</td>
<td>TL</td>
<td>0.034</td>
<td>0.206</td>
<td>0.069</td>
<td>0.038</td>
<td>0.196</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>0.583</td>
<td>0.018</td>
<td>0.024</td>
<td>0.041</td>
<td>0.884</td>
</tr>
<tr>
<td>Break imp</td>
<td>TL</td>
<td>0.341</td>
<td>0.417</td>
<td>0.880</td>
<td>0.723</td>
<td>0.127</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>0.712</td>
<td>0.037</td>
<td>0.028</td>
<td>0.044</td>
<td>0.981</td>
</tr>
<tr>
<td>Break time</td>
<td>TL</td>
<td>0.477</td>
<td>0.919</td>
<td>0.848</td>
<td>0.945</td>
<td>0.116</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>0.611</td>
<td>0.826</td>
<td>0.607</td>
<td>0.651</td>
<td>0.983</td>
</tr>
<tr>
<td>Prop peak</td>
<td>TL</td>
<td>0.007</td>
<td>0.081</td>
<td>0.253</td>
<td>0.280</td>
<td>0.823</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>0.384</td>
<td>0.686</td>
<td>0.998</td>
<td>0.795</td>
<td>0.235</td>
</tr>
<tr>
<td>Prop imp</td>
<td>TL</td>
<td>0.366</td>
<td>0.289</td>
<td>0.254</td>
<td>0.258</td>
<td>0.689</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>0.277</td>
<td>0.146</td>
<td>0.369</td>
<td>0.453</td>
<td>0.550</td>
</tr>
<tr>
<td>Prop time</td>
<td>TL</td>
<td>&lt;0.001</td>
<td>0.001</td>
<td>0.018</td>
<td>0.012</td>
<td>0.166</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>&lt;0.001</td>
<td>0.003</td>
<td>0.012</td>
<td>0.007</td>
<td>0.558</td>
</tr>
</tbody>
</table>

Differences between breeds when initial data was used and when ANCOVA was used to eliminate the variance arising from relative velocity (Vrel), functional limb length (Funct), relative velocity and functional limb length (Vrel+Funct), and body weight (Weight). The effect of relative velocity and functional limb length was tested from initial data, where forces, impulses, and slopes were expressed as percentage of body weight, and the effect of body weight was tested from un-normalized raw data. The level of significance was set at P < 0.05, and P-values significantly different between breeds are indicated in boldface. For abbreviations, see Table 4.
Study IV

The results of force plate analysis were available for 41 dogs (study group). Body weight, trotting velocity, or acceleration did not differ significantly between the study group or subgroup 1 dogs and the control group dogs, between the surgically treated and the contralateral limbs, or between the surgical technique groups.

When force plate results for the study group were evaluated, no significant differences emerged when comparing the surgically treated limb with the contralateral pelvic limb or the pelvic limbs of control dogs. In subgroup 1, the surgically treated limbs had a significantly lower PVF (P = 0.040) and DPVF (P = 0.005) than the contralateral pelvic limbs, but no significant differences were found when surgically treated limbs were compared with control dog limbs (Table 6).

The determined SI cut-off values were 7.1% for PVF and 8.1% for VI. To improve the specificity of the cut-off value, they were rounded up to 8% and 9%, respectively. Based on these cut-off values, the SI for PVF was <8% in 13 dogs (61.9%), indicating normal gait symmetry, and ≥ 8% in 7 dogs (33.3%), indicating lameness. In one dog, the SI indicated lameness of the contralateral pelvic limb (≤ -8%). Similarly, the SI for VI was <9% in 15 dogs (71.4%), indicating normal gait symmetry, and ≥ 9% in 6 dogs (28.6%), indicating lameness. Of the 7 dogs in which one or both SIs indicated lameness, 3 had been treated with intracapsular, 2 with extracapsular, and 2 with osteotomy techniques.

When the force plate results of the different surgical technique groups were evaluated, no significant differences were found in study group between intracapsular, extracapsular, and osteotomy techniques or in study group or subgroup 1 when surgically treated limbs in each technique group were compared with pelvic limbs in control dogs (Table 6). Subgroup 1 dogs that had been treated with the intracapsular technique had significantly lower DPVF in the surgically treated limb than the dogs treated with osteotomy techniques (P = 0.044). Also the dogs treated with the intracapsular technique had significantly lower VI (P = 0.035) and DPVF (P = 0.018) in the surgically treated limb than in their contralateral pelvic limb (Table 6). No significant differences were seen when limbs treated with the osteotomy technique were compared with their contralateral pelvic limb. The number of dogs treated with the extracapsular technique (n=3) was too low to be analyzed.
Results

Table 6 Mean ± SD results of force plate analysis and static weight bearing in subgroup 1 dogs, separately in intracapsular, extracapsular, and osteotomy surgical technique groups, and in control dogs.

<table>
<thead>
<tr>
<th>Subgroup 1 (n=21)</th>
<th>Intra (n=7)</th>
<th>Extra (n=3)</th>
<th>Osteo (n=11)</th>
<th>Control group (n=21)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>STPL</td>
<td>CPL</td>
<td>STPL</td>
<td>CPL</td>
</tr>
<tr>
<td>Force plate analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PVF (% N/N)</td>
<td>70.6 ±7.0#</td>
<td>75.3 ±7.3</td>
<td>67.2 ±7.6</td>
<td>75.1 ±6.7</td>
</tr>
<tr>
<td>VI (%Ns/N)</td>
<td>8.7 ±1.2#</td>
<td>9.4 ±1.0</td>
<td>8.3 ±0.9#</td>
<td>9.5 ±1.0</td>
</tr>
<tr>
<td>DPVF (%)</td>
<td>18.5 ±1.3#</td>
<td>19.8 ±1.4</td>
<td>17.8 ±1.5#</td>
<td>19.9 ±1.3</td>
</tr>
<tr>
<td>Static weight bearing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SWB (%)</td>
<td>15.5 ±5.6#</td>
<td>19.7 ±3.6</td>
<td>13.8 ±7.3#</td>
<td>21.2 ±3.3</td>
</tr>
</tbody>
</table>

# Significant (P < 0.05) difference present between the surgically treated and the contralateral pelvic limb.* Significant (P < 0.05) difference present in the measured value between the limbs treated with intracapsular and osteotomy techniques. Forces and impulses are reported as percentages of body weight.

STPL, surgically treated pelvic limb; CPL, contralateral pelvic limb; PL, pelvic limb, PVF, peak vertical force; VI, vertical impulse; DPVF, percentage distribution of peak vertical force; SWB(%), static weight bearing reported as percentages proportional to body weight; Intra, intracapsular; Extra, extracapsular; Osteo, osteotomy; NA: not analysed due to low number of dogs in the extracapsular group.

5.3.4 Physiotherapeutic examination (III, IV)

Study III

The mean ± SD SWB% in pelvic limbs of healthy control dogs was 17.7 ± 2.8 %, and the mean ± SD Diff SWB% between pelvic limbs in healthy control dogs was 3.3 ± 2.7 %, resulting in a 6% cut-off value as the normal limit. No significant difference existed in SWB% or Diff SWB% between the Rottweiler and Labrador breeds.

Study IV

The qmSWB was not evaluated in 2 dogs due to lack of cooperation, and the PROM was not evaluated in 3 dogs for the same reason and in one dog because of a concurrent orthopedic problem in the tarsal joint.

When results of qmSWB were evaluated, dogs in both the study group and subgroup 1 had a significantly lower SWB% in the surgically treated limb than in the contralateral pelvic limb (P = 0.010 and P = 0.006, respectively) (Table 6). Based on the DiffSWB cut-off value (Study III), 13 of 21 dogs (61.9%) had symmetrical weight bearing, 6 (28.6%) had decreased weight bearing in the surgically treated limb, and 2 (9.5%) bore less weight on the contralateral pelvic limb. Of the dogs with decreased weight bearing in the surgically treated limb, 3 had been treated with intracapsular and 3 with osteotomy techniques.
In the study group, no significant differences emerged when SWB in the surgically treated limb was compared between surgical techniques or separately in each surgical technique group with either the contralateral limb or the control dogs’ limbs. Similarly, in subgroup 1 dogs, no significant differences were found between surgical techniques. When each surgical technique group in subgroup 1 was evaluated separately and surgically treated limbs were compared with the contralateral and control dog limbs, no significant differences were observed in the osteotomy group, but in the intracapsular group the SWB% in the surgically treated limb was significantly lower than that in the contralateral limb \( (P = 0.030) \) (Table 6). The number of dogs in the extracapsular group \( (n=3) \) was too low to be analyzed.

In visual evaluations of functional AROM, the most frequent findings were in sitting position. In subgroup 1, a decreased flexion of the tarsal joint was seen in 12 dogs (57.1%; 2 intracapsular, 10 osteotomy), a decreased flexion of the stifle joint in 10 dogs (47.6%; 2 intracapsular, 1 extracapsular, 7 osteotomy), and an abduction of the limb in 9 dogs (42.9%, 1 intracapsular, 1 extracapsular, 7 osteotomy). Except for one dog, the positive findings were always localized in the surgically treated limbs. Thrust from the sitting position was weaker in the surgically treated limb in 14 dogs (66.7%; 3 intracapsular, 1 extracapsular, 10 osteotomy). When evaluating muscle atrophy in subgroup 1, altogether 16 dogs (76.2%) had decreased muscle mass of the surgically treated pelvic limb on palpation (5 intracapsular, 2 extracapsular, 9 osteotomy), while only 4 dogs had symmetrical muscle mass, and one dog had decreased muscle mass in the contralateral limb.

When PROMs of surgically treated limbs were compared with those of contralateral limbs, stifle extension angles \( (P < 0.001) \) were significantly lower and stifle flexion angles \( (P < 0.001) \) were significantly higher (loss of flexion) in the surgically treated limb (Table 7). Similar differences also emerged in the intracapsular and osteotomy groups when each surgical technique was evaluated separately and the surgically treated limb was compared with the contralateral limb. In the extracapsular group, stifle flexion angles \( (P=0.045) \) were significantly higher (loss of flexion) in surgically treated limbs than in contralateral limbs. No significant differences were found between the surgical techniques.

**Table 7** Mean ± SD stifle joint extension and flexion angles and percentages of surgically treated limbs relative to contralateral limbs in subgroup 2 dogs, and separately in intracapsular, extracapsular, and osteotomy surgical technique groups.

<table>
<thead>
<tr>
<th></th>
<th>Subgroup 2 ( (n=33) )</th>
<th>Intra ( (n=11) )</th>
<th>Extra ( (n=6) )</th>
<th>Osteo ( (n=16) )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>STPL CPL</td>
<td>STPL CPL</td>
<td>STPL CPL</td>
<td>STPL CPL</td>
</tr>
<tr>
<td><strong>Stifle extension</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degr</td>
<td>149.2 ±8.6*</td>
<td>160.3 ±6.6</td>
<td>148.2 ±7.5*</td>
<td>163.0 ±2.5</td>
</tr>
<tr>
<td>%</td>
<td>93.1</td>
<td>90.9</td>
<td>93.2</td>
<td>94.6</td>
</tr>
<tr>
<td><strong>Stifle flexion</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degr</td>
<td>47.9 ±7.2*</td>
<td>41.1 ±6.5</td>
<td>48.0 ±5.4*</td>
<td>40.3 ±8.5</td>
</tr>
<tr>
<td>%</td>
<td>95.1</td>
<td>94.5</td>
<td>95.9</td>
<td>95.2</td>
</tr>
</tbody>
</table>

*Significant \( (P < 0.05) \) difference present between the surgically treated limb and the contralateral pelvic limb. STPL, surgically treated pelvic limb; CPL, contralateral pelvic limb; Degr, degrees. Intra, intracapsular; Extra, extracapsular; Osteo, osteotomy.
Discussion

6 Challenges of outcome measures

Force plate analysis has been considered the gold standard for objective assessment of limb function (Budsberg et al. 1987, Rumph et al. 1994). To enable the comparison of force plate values between individual patients or patient groups, ground reaction forces and impulses are usually expressed as a percentage of body weight and the subject velocity and acceleration are limited to a narrow range.

In Study I, the ground reaction forces in healthy Rottweilers differed significantly from force plate data obtained from healthy Labradors when standard normalization by linear scaling to body weight, given by the software, was used. The body weight and anatomic measurements of the Rottweilers were also significantly larger than in Labrador Retrievers. When breeds were combined, body weight correlated with all force plate values that were significantly different between breeds. A similar correlation of body weight with normalized ground reaction forces has been reported in studies using heterogeneous populations of dogs with large variation in body weight or breed (Budsberg et al. 1987, Voss et al. 2007). Although the absolute trotting velocity was controlled, the calculated relative velocity, influenced by the limb length, differed significantly between the breeds in Study I, meaning that the smaller Labradors actually traveled at a faster relative velocity than taller Rottweilers.

To evaluate the cause for the breed differences, ANCOVA was used to eliminate variance associated with relative velocity, functional limb length, and body weight. Based on the results, the ground reaction force differences between breeds were attributable to differences in conformation and the related changes to relative velocity and body weight of the dog. ANCOVA appeared to remove the effect of body weight more efficiently than the standard normalization. Recently, also other studies have focused on evaluating the effect of body conformation or body weight on ground reaction forces (Bertram et al. 2000, Voss et al. 2010, Voss et al. 2011, Krotscheck et al. 2014), and normalization methods to account for the conformational differences have been proposed (Voss et al. 2010).

These studies indicate that when comparing dog groups with differing body weights or sizes within and between research studies the standard methods of normalization for ground reaction data may be inadequate and this can cause bias in the study results. One option to overcome the problems related to comparison of heterogeneous populations of dogs is to use symmetry or asymmetry indices (SI or ASI). Several SI or ASI formulas have been introduced (Herzog et al. 1989, Budsberg et al. 1993). In Study IV, the SIs were calculated for healthy and surgically treated dogs and the values of the healthy dogs were used to determine a cut-off value for differentiation between normal gait symmetry and lameness. Also other reports using SIs to evaluate the outcome after CCL repair have been published (Voss et al. 2008, Böddeker et al. 2012, Nelson et al. 2012). In order to use these indices reliably, the contralateral limb should be free of orthopedic problems.

In Study IV, a physiotherapeutic examination from the perspective of the professional veterinary physiotherapist was included in the evaluation methods. The evaluation concentrated on the stifle joints, and, in addition to measurements of stifle joint ROM and evaluation of muscle atrophy, also new methods, such as SWB, AROM during sitting and lying positions, and thrust from the ground, were included. The assessments of AROM and thrust from the ground were targeted to evaluate the functionality of the patient, in other words, the dog’s ability to perform
the activities of daily living (e.g. sit or lie down, get up from sitting or lying position, climb stairs, get into a car). Although dynamic weight bearing has been evaluated in many CCL studies, SWB measurements have not been reported before in assessment of surgical outcome after CCL repair. In Study III, a simple and cost-effective method for measurement of SWB was described, and normal variance for the difference between the pelvic limbs was set.

### 6.2 Chronic pain in surgically treated dogs

Based on the owner evaluation in Study II, after a mean period of 2.7 years, approximately 31% of the surgically treated dogs had a HCPI value ≥ 12, indicating pain. Also approximately 32% of the clinically evaluated dogs in Study IV showed a pain response to extension/ flexion of the surgically treated stifl e joint. The signs of pain in these dogs may be related to the progression of osteoarthritis. Osteoarthritis can cause chronic pain and discomfort and have significant impact on a patient's quality of life (Lamont et al. 2000). Chronic pain might also be related to poor preoperative condition of the surgically treated stifl e joint or to surgical complication such as technical error during surgery, implant failure and/or migration, late meniscal tear, patellar luxation, septic arthritis, suture infection or bone/joint neoplasia. Innes et al. (2000) reported that patients with meniscal injury diagnosed during CCL repair had significantly lower long-term levels of exercise and higher levels of disability and inactivity stiffness than in patients without a meniscal injury. In study I, the HCPI had no significant association with the duration of the clinical signs before surgery, or presence or absence of the meniscal tear in surgery, but the condition of the meniscus was reported only in 50 % of the patients. In 5.9 % of dogs the cruciate ligament-deficient limb underwent surgery more than once with a single or multiple techniques. Based on owner evaluation, these dogs were less willing to bear weight on the surgically treated limb at follow-up than dogs that underwent surgery only once, but no significant differences were found in HCPI values between the groups.

Chronic pain has not been extensively studied in CCL-treated patients. The focus of the postoperative studies has been on evaluation of dynamic weight bearing, which indirectly may measure pain, but can also be affected by other factors such as limitations in range of motion or loss of muscle mass of the surgically treated limb. In addition, objective evaluation of pain is difficult and orthopedic outcome assessment has long lacked appropriate tools for pain assessment.

Validated owner-reported evaluation methods targeted for evaluation of OA and chronic pain have been used in several CCL studies (Innes et al. 2000, Boyd et al. 2007, Corr and Brown 2007, Renwick et al. 2009, Gordon-Evans et al. 2013). However, these questionnaires have mainly focused on evaluating improvement of the dog's condition postoperatively and comparing improvement between the surgical techniques, not evaluating whether the dog experiences pain or not. One option for evaluation of pain is to use VAS-based scores. A drawback to owner-reported VAS for pain is that if owners are not trained they have difficulties in recognizing signs of pain, and thus, may underestimate it (Hielm-Björkman et al. 2011). Christopher et al. (2013) used owner-reported VAS to evaluate degree of pain in surgically treated dogs after > 1 year postoperatively. With a scale from 0 to 100, the mean VAS of pain ranged between 12 and 17, depending on the surgical technique used. When only presence or absence of pain was evaluated, 44-61% of dogs were judged by their owners to have at least some degree of long-term pain.

Although owner assessments indicate that many CCL patients experience some degree of long-term pain after surgery, only 12% of the dogs in Study II received NSAIDs for the treatment
of pain arising from the surgically treated limb. This may reflect the failure of the owners to recognize signs of pain in their dogs. Chronic pain may cause very subtle changes in demeanor, general mood, and willingness to move, which can be difficult to detect and understand as a pain response. It is therefore important that clients are informed about the long-term prognosis of CCL disease and are educated to recognize the signs of pain and to treat the pain accordingly.

When the owner assessment of surgical outcome was evaluated, dogs with good outcomes had a mean HCPI indicative of chronic pain, whereas dogs with excellent outcomes had mean values at the level of healthy dogs. In studies evaluating the outcomes of CCL surgery, excellent and good outcomes are often combined, generally resulting in success rates of >90% (Elkins et al. 1991, Hoffmann et al. 2006, Corr and Brown 2007, Stein and Schmoekel 2008). Based on findings in Study II, this kind of generalization may give a false impression of a pain-free outcome and should not be used.

### 6.3 Long-term limb function after cranial cruciate ligament surgery

In Study IV, when evaluated at a mean of 2.8 years after the CCL surgery, the average dynamic and static weight bearing of the surgically treated limbs had returned to the level of healthy limbs. In force plate analysis, no significant differences were found in ground reaction forces between the surgically treated pelvic limbs of CCL dogs and the control limbs of healthy dogs. The PVF of surgically treated limbs was significantly and approximately 5% lower than the corresponding value for the contralateral pelvic limbs, but load distribution from injured to contralateral pelvic limb may artificially increase the difference between limbs (Rumph et al. 1993). Furthermore, the PVF of the surgically treated limbs was only 1.6% lower than the corresponding value for the control dog limbs, and mean VI was the same in surgically treated and control dog limbs. When static weight bearing was evaluated, a similar trend was observed. Although the SWB% of the surgically treated limbs was significantly and approximately 4% lower than that of contralateral limbs, the difference between surgically treated and control dog limbs was only 2.2%. It can be assumed that, similar to dynamic weight bearing, load distribution to contralateral limbs occurs also when measuring SWB. When clinical importance of observed differences is evaluated, these result indicate that the mean differences between the surgically treated and healthy limbs were minor and without clinical relevance.

Although the average dynamic and static weight bearing returned to the level of healthy limbs, in approximately 30% of dogs the SIs for PVF and VI indicated lameness and the DiffSWB% indicated decreased weight bearing in the surgically treated limb, thus reflecting a clinically relevant problem in weight bearing in these dogs and also revealing considerable variation between the evaluated dogs. By using the cut-off values for SIs and DiffSWB%, more differences were revealed than those discovered when the mean ground reaction forces between the surgically treated and healthy limbs were compared.

Interestingly, also compensations of AROM were seen in 40-50% of surgically treated limbs and weakness in thrust from the ground in two-thirds of limbs. Although subjective, these evaluations give clinically relevant information on how dogs function in their normal daily activities. When goniometric results of surgically treated limbs were evaluated, a statistically significant loss of 5% in flexion and 7% in extension of the stifle joints was seen. The clinical relevance of these changes is unknown and can only be speculated. Jandi et al. (2007) reported
that loss of flexion or extension ≥ 10° was associated with higher lameness scores, but in Study IV no correlation between goniometric results and dynamic or static weight bearing was found.

Few studies have evaluated the long-term (>1 year) return of limb function to the preinjury level by using objective evaluation methods (Au et al. 2010, Moeller et al. 2010). Similar to the results of Study IV, Moeller et al. (2010) reported that stifle joint extension and flexion angles of surgically treated limbs remained significantly decreased relative to contralateral joints at 1-5 years after TPLO surgery. Also in another study the stifle joint ROM angles in surgically treated limbs were below the preoperative values 2 years after TPLO and extracapsular repair (Au et al. 2010). Several short- or medium-term studies have shown that after the initial improvement of ROM angles with surgery, stifle joint ROM starts to decrease (Jerram et al. 2005, Bruce et al. 2007, Au et al. 2010, Gordon-Evans et al. 2013). The most probable cause for the decrease of ROM over time is the progression of OA, causing functional impairment due to pain and mechanical restriction of joint mobility related to fibrous tissue and new bone formation in the joint and its periarticular tissues. Another explanation might be that many dogs undergo postoperative rehabilitation, which has been shown to improve the ROM in the affected joint. After rehabilitation is completed and without continuing rehabilitation exercises, the ROM may start decreasing.

No long-term force plate studies evaluating return of limb function to the level of healthy limbs have been reported. However, force plate analysis results of the Study IV are in accordance with previous short- and medium-term studies, where the average dynamic weight bearing in the surgically treated limb was at the level of contralateral or control dog limbs 7 months after extracapsular repair (Budsberg et al. 1988), 4 and 12 months after TPLO surgery (Böddeker et al. 2012, Nelson et al. 2013), and 2-54 months after TTA surgery (Skinner et al. 2013).

In summary, although force plate analysis provides objective and reliable information about dynamic weight bearing and limb function, it may be inadequate as the sole method for outcome assessment. Evaluation of functional outcome after CCL surgery should be based on several outcome assessment methods combining different aspects of limb function.

6.4 Comparison of surgical techniques

Intracapsular, extracapsular, and osteotomy techniques were compared. When owner evaluation with HCPI was used in Study II, no significant differences emerged in long-term chronic pain between the techniques. Occurrence of chronic pain after intracapsular or extracapsular fabellotibial suture techniques has not been compared before with other techniques, but in a recent study comparing TPLO, TTA, and TightRope techniques no significant differences were found in owner-reported VAS for long-term pain (Christopher et al. 2013). In Study II, owners’ perceptions of long-term frequency of lameness and willingness to bear weight on the surgically treated limb were similar between the different technique groups. However, the owners’ opinion on duration of postoperative lameness was that it was shorter in dogs treated with osteotomy techniques than with the intracapsular technique. No significant difference was found between the osteotomy and the extracapsular techniques. Although the owners’ ability to recollect the time of surgery and postoperative recovery must be interpreted cautiously, our findings do support the general subjective opinion that weight bearing is seen earlier in dogs treated with osteotomy techniques. A comparison between osteotomy techniques and the intracapsular treatment such as the one presented in our study has not been done before, but two recent force
plate studies have suggested that TPLO leads to faster recovery than the extracapsular technique (Böddeker et al. 2012, Nelson et al. 2013).

In Study IV, the dogs treated with the intracapsular technique had significantly lower DPVF in the surgically treated limb than the dogs treated with the osteotomy techniques. No other significant differences emerged between surgical technique groups when dynamic and static weight bearing or goniometric results were evaluated. However, when each technique group was evaluated separately, operated limbs of dogs in the intracapsular group had significantly lower VI, DPVF, and SWB% values than contralateral pelvic limbs. In the osteotomy group, no significant differences were seen in dynamic or static weight bearing between surgically treated and contralateral limbs. In goniometry, stifl e joint extension and flexion angles were decreased relative to the contralateral limb in both the intracapsular and osteotomy groups. Unfortunately, the low number of dogs in the extracapsular group did not allow statistical comparison. In summary, although the evaluated groups were small and weight distribution from affected limb to contralateral limb must be taken into account, the long-term average limb function in dogs treated with osteotomy techniques may with a higher probability be indistinguishable from healthy limbs relative to dogs treated with the intracapsular technique. Parallel results were reported also in two previous short-term force plate studies. The limb function after intracapsular surgery remained inferior to limb function after TPLO and extracapsular surgery 6 months postoperatively (Conzemius et al. 2006), and in another experimental study limb function after intracapsular surgery remained inferior to preoperative function at a 20-week follow-up (Jevens et al. 1996).

In Study IV, the OA severity was evaluated with radiography and stifl e joint palpation. The severity of radiographic OA in the surgically treated limb was lower in the osteotomy group than in the intracapsular group, and the dogs treated with osteotomy techniques had less crepitation in the surgically treated limb than dogs treated with intra- or extracapsular techniques. However, the preoperative radiographs were not available and potential initial differences between the surgical techniques may have affected these results. On the other hand, it could be speculated that the preoperative differences in radiographic OA between groups might level off over time. This has been reported in two studies, where the preoperative amount of OA was found to correlate negatively with the progression of OA postoperatively, meaning that dogs with severe pre-existing OA showed less potential for OA to worsen relative to dogs with only minor pre-existing OA (Lineberger et al. 2005, Hurley et al. 2007). As mentioned earlier, the clinical significance of radiographic OA has been questioned (Gordon et al. 2003). Albeit of minor significance, these findings are in accordance with the results of dynamic and static weight bearing and are thus worth mentioning.

6.5 Strengths and limitations of the study

These studies yielded objective evidence regarding a clinically important problem, the surgical outcome of CCL disease. A true long-term evaluation was conducted, with a time interval of 1.3 to 4.5 years between the surgery and the evaluations. Multiple approaches evaluating different aspects of the surgical outcome were used. In addition to traditional subjective evaluation methods, such as visual lameness evaluation, palpatory findings and measurement of radiographic OA, objective and validated assessment tools, including HCPI, force plate analysis, and goniometry, were used. As a new aspect, physiotherapeutic examination concentrating on
stifle joints was included, and thus, also the functionality of the surgically treated limbs was taken into account. In addition, a healthy control group was included to obtain reference values.

The main limitation of Studies II and IV was their retrospective nature. The patient material was very heterogeneous, with many possible confounding factors. As this was not a prospective study, variables such as conformation, body weight and age of the dog, duration of clinical signs before surgery, completeness of the CCL tear, meniscal pathology and treatment, and postoperative rehabilitation and medications were not standardized, and these may have affected the surgical outcome. In addition, it's possible that patient material included in the study did not truly reflect the original population of 507 dogs because factors such as outcome of surgery may have affected the owners’ willingness to answer the questionnaire, either positively or negatively. Also, at the time the dogs were treated, postoperative rehabilitation was not yet widely used. Thus, the number of dogs receiving postoperative physiotherapy, which is presently recommended for all CCL-deficient dogs, was low. Although it would have been ideal to perform a prospective, randomized, controlled clinical trial with the effect of confounding factors minimized, the circumstances in these studies do reflect a real-life situation, where age, weight, conformation, concurrent health issues of the patient, owner compliance, and postoperative treatment often vary in the patient material, and thus are representative of dogs typically predisposed to CCL injury. This material can well be used to evaluate general surgical outcome, but when comparing surgical techniques, the confounding factors may cause bias in the results.

Although over 250 dogs were evaluated by the owners in Study II, the number of dogs in the clinical evaluation (Study IV) was unfortunately low. The body weight limitations set by the force plate and other concurrent orthopedic problems that were diagnosed reduced the number of dogs eligible for the force plate, SWB, and AROM evaluations. To detect statistical significance in PVF between the surgically treated and control dogs using the data generated from this study, 400 dogs would have been needed (using $\alpha = 0.05$ and 80% power). On the other hand, it may be speculated that even had statistical significance been shown, a difference of 1.6% in PVF between the surgically treated and control dog limbs might not have been clinically significant.

The anatomic measurements were available only for healthy control dogs (Study I) and were not measured for the surgically treated dogs in Study IV. Thus, the possible effect of conformation on differences in force plate data between the control and study groups could not be accounted for and only standard normalization of forces and impulses to body weight was used. However, there were no significant differences in mean body weight between control and study group dogs, and, although including many breeds, the most common breeds also in the study group were Labrador Retrievers and Rottweilers. As a compromise, the force plate results and measurements of SWB were compared with both the control dog and the contralateral limbs, and after taking into account the possible weight distribution, the results were in accordance with each other.

In Studies I, III, and IV, the healthy control dogs were not radiographed. Orthopedic examination and previous screening for hip dysplasia were relied on to exclude any orthopedic problems. Neither the healthy control dogs nor the study group dogs were habituated in advance to the gait analysis routine, and only one force plate was used during the measurements. The SWB measurements were performed only on pelvic limbs, and possible compensation in weight bearing towards the thoracic limbs was ignored. In addition, the muscle mass symmetry was evaluated manually, and no quantitative measurement with a tape measure was included.
Based on these studies, the following conclusions can be drawn:

1. The ground reaction forces in Rottweilers differed significantly from the data obtained for Labrador Retrievers when standard methods of normalization were used. The differences were attributable to a difference in conformation and body weight between the breeds.

2. A simple, cost-effective tool for measurement of static weight bearing in pelvic limbs was described. Based on the calculated mean ± SD difference between the pelvic limbs in healthy dogs, a cut-off value of 6% for differentiating between normal and decreased static weight bearing was set.

3. According to the Helsinki Chronic Pain Index, approximately 31% of 206 dogs had signs of chronic pain evaluated retrospectively at a mean of 2.7 years after CCL surgery. The owner assessments revealed no significant differences between the surgical techniques in long-term outcome.

4. While I acknowledge the retrospective nature of study IV and its small sample size, some findings are still worth reporting. At a mean of 2.8 years after CCL surgery, the average dynamic and static weight bearing in surgically treated limbs had returned to the level of healthy limbs. However, when symmetry of weight bearing was evaluated using cut-off values, approximately 30% of dogs had decreased dynamic and static weight bearing in the surgically treated limbs. Also, goniometric angles of the surgically treated limbs remained inferior to those of healthy limbs, and impairment of the active range of motion was frequently observed. Ground reaction forces may be inadequate as the sole method for evaluating functional outcome after CCL repair. Based on differences in dynamic and static weight bearing, osteotomy techniques may offer long-term limb function that is superior to that of the intracapsular technique.
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