Selected clinical studies on canine joint function and morphology using computerized gait analysis and diagnostic imaging

THESIS

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Dedicated to my family
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1. Introduction

The high prevalence of orthopedic diseases in the dog makes the evaluation of functional and morphologic characteristics of joint disease in this species an important and fascinating area of research. For many years the study of lameness caused by joint disease was performed using subjective methods of evaluation, including lameness scoring systems, which have been proven to lack reliability (WAXMAN et al. 2008; BURTON et al. 2009). Besides, even the most experienced clinician has limited ability to detect subtle changes in movement (OFF and MATIS 1997a, b; GILLETTE and ANGLE 2008). Therefore, special diagnostic techniques, such as computerized (kinetic and kinematic) gait analysis, are needed to objectively and quantitatively evaluate the forces (kinetics) and movements (kinematics) involved in locomotion (DECAMP 1997; MCLAUGHLIN 2001).

Kinetic gait analysis can be used to obtain non-invasive, objective, and quantitative assessment of the forces occurring between the foot and the surface during the stance phase of the stride (MCLAUGHLIN 2001). Vertical (Fz) forces indicate the magnitude of the weight bearing and craniocaudal (Fy) forces represent breaking and propulsion forces (progression of the animal). Additionally, mediolateral (Fx) forces can be measured for each limb (BUDSBERG et al. 1987; DECAMP 1997; GILLETTE and ANGLE 2008) (Figure 1). These forces are more commonly measured in Newtons (N), and are normalized to a percentage of body weight (% BW), in order to make them comparable between animals (BUDSBERG et al. 1993; BOCKSTAHLER et al. 2007). Kinetic data allows the measurement of individual loads applied by each limb limb at the desired gate pace (walking, trotting or running). Afterwards, the calculation of limb symmetry (symmetry index - SI) and load redistribution (LR) is possible, which have been commonly used to measure recovery and compensation in the analysis of several orthopaedic diseases, such as cranial cruciate ligament rupture (BUDSBERG et al. 1988; DECAMP et al. 1996; BÖDDEKER et al. 2012), hip dysplasia (BRADEN et al. 2004; FANCHON and GRANDJEAN 2007), and fragmented medial coronoid process (BURTON et al. 2008; BURTON et al. 2009).
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Figure 1. Screenshot of a gait analysis session. Fx, Fy and Fz forces detected by the force plates (in this example, only for the forelimbs).

To measure the loads, both force plates (JEVENS et al. 1993; BERTRAM et al. 2000; MADORE et al. 2007) and instrumented treadmills (OFF and MATIS 1997b; BOCKSTAHLER et al. 2007; BÖDDEKER et al. 2012) can be used (Figures 2 and 3). Instrumented treadmills have many advantages, including the possibility to control important parameters such as speed, measure simultaneously all four limb forces in a reproducible way, and the need of a smaller laboratory (OFF and MATIS 1997a, b; BELLI et al. 2001; BREBNER et al. 2006; BOCKSTAHLER et al. 2007). Besides, gait patterns are very similar when comparing the two systems (BÖDDEKER et al. 2010).

Kinematic gait analysis using high-speed infrared cameras (Figure 4) and retro-reflective markers positioned on anatomical landmarks of the canine body (Figure 3) can serve as a tool to detect and quantify changes in joint angles, step length or step velocity (HOTTINGER et al. 1996; DECAMP 1997; GILLETTE and ANGLE 2008).
Figure 2. Example of patient walking on a runway, with a force plate embedded in it. The picture was taken in the old gait laboratory of the University of Veterinary Medicine Hannover, Foundation.

Figure 3. Example of a dog walking on an instrumented treadmill, with four independent belts. Picture taken at the gait laboratory of the University of Veterinary Medicine Hannover, Foundation. Note the retro-reflective markers placed on the patient.
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The cameras detect marker movement in a 3-dimensional (3-D) space, allowing the reconstruction of the patients' movement (Figure 5). Initially, kinematics were used to characterize the normal movement pattern of different breeds (DECAMP et al. 1993; HOTTINGER et al. 1996). More recently, the kinematic analysis of joint disease has been performed to objectively evaluate surgical success in the stifle (BÖDDEKER et al. 2012), hip (BRADEN et al. 2004), and elbow (BURTON et al. 2011), among other joints.

![Figure 4](image)

**Figure 4:** Gait laboratory of the University of Veterinary Medicine Hannover, Foundation. Note the infrared cameras (3 of 6) located around the treadmill (arrows).

Even though data obtained using kinetic and kinematic gait analysis can be correlated with other diagnostic modalities, this is carried out very seldom: only one study assessed computerized gait analysis combined with scintigraphy and computed tomography (CT) for the diagnosis of disease of the palmar sesamoid bones in dogs (MURGIA et al. 2005). In that study, CT allowed the visualization of lesions that were overlooked on plain radiographs. CT was used in one of the studies included in this thesis, as it is one of the preferred diagnostic methods to rule out different diseases, including medial coronoid process disease (MCPD) (Figure 6). CT allows multislice, multidirectional cross-sectional imaging, alleviating the problem of bone superimposition associated with radiography (MOORES et al. 2008; COOK and COOK 2009). CT also allows the evaluation of articular subchondral bone; therefore,
lesions such as sclerosis, fissures, necrosis, cysts, and fragmentation are detectable (COOK and COOK 2009).

Figure 5. Screenshot of a gait analysis session. The 3-D perspective illustrates the retro-reflective markers, as detected by the infrared cameras.

Figure 6. Patient suffering from medial coronoid process disease (MCPD) being imaged in the CT scan (Philips Brilliance 64 CT Scanner: Philips Healthcare, Hamburg, Germany) of the Small Animal Hospital, University of Veterinary Medicine Hannover.
However, the nature and extent of cartilage lesions within the joint cannot be evaluated with this diagnostic tool (MOORES et al. 2008) and other diagnostic techniques, such as magnetic resonance imaging (MRI) are therefore needed (Figure 7).

![Figure 7](image.jpg)

**Figure 7.** Patient suffering from medial coronoid process disease (MCPD) being imaged in the magnetic resonance (MR) scan (Philips Achieva 3.0T X-series MRI. Philips Healthcare, Hamburg, Germany) of the Small Animal Hospital, University of Veterinary Medicine Hannover.

Magnetic resonance (MR) is a relatively new diagnostic imaging modality in veterinary medicine. In human orthopaedics, MRI is the preferred diagnostic tool for certain joint diseases, such as meniscal and ligament tears (CRAWFORD et al. 2007). Low-field (LF) MRI has been used and considered valuable to evaluate the appearance of normal (BAIRD et al. 1998) and pathologic stifle joints in dogs (KONAR et al. 2005b; MARTIG et al. 2006; WINEGARDNER et al. 2007). High-field (HF) MRI has also been used to assess cartilage volume, cartilage defect and lesions on the subchondral bone of canine knees with experimentally induced osteoarthritis (OA) (BOILEAU et al. 2008). In that report, the authors concluded that MRI is useful to assess the evolution of structural changes in experimental osteoarthritis (OA); however, MR images have still limitations: one study reported that the accurate assessment of cartilage coverage of the ulnar trochlear notch (UTN) using HF MRI in post-mortem specimens was promising in mid-sized to giant breeds, but difficult in small and chondrodystrophic breeds (PROBST et al. 2008).
The general objective of this thesis was to investigate three common clinical conditions in dogs which directly affect joint function, using a combination of diagnostic techniques in order to assess morphologic and functional changes. Thus, the specific objectives of this work were:

1. To characterize the recovery outcome of dogs undergoing a hind limb amputation. In order to evaluate the motion and weight bearing characteristics, as well as the duration of adaptation to the three-legged gait, kinematic and kinetic analyses were carried out. Furthermore, MR images of the remaining contralateral stifle joint were made before and 4 months after amputation, in order to investigate possible changes in joint morphology. It was intended to see if there was a correlation between the functional (kinetic and kinematic gait analysis) and morphologic (MR) characteristics of the stifle joint in the contralateral hind limb, due to a hypothetic weight bearing overload of this limb. Finally, the subjective impressions of the owner with regard to the recovery of the patient were gathered and compared with the objective results from the gait analysis. The results of this part of the thesis could be useful to properly advise owners facing the decision to have their dog amputated or not.

2. To objectively evaluate forelimb load as well as elbow function and morphology before and after the arthroscopic treatment of unilateral MCPD in clinical patients, using computerized gait analysis, goniometry and radiography. CT was used to ensure that one forelimb remained healthy. Additionally, it was aimed to determine if the functional parameters (kinetic and kinematic gait analysis and goniometry) correlate with the morphologic (radiography) parameters. This part of the thesis could be useful to adequately evaluate the general belief of excellent recovery after the arthroscopic treatment of MCPD.

3. Finally, to determine the agreement between 3 T MR images and the actual surgical findings, with regard to the diagnosis of joint lesions associated with a CCLR in dogs in a clinical setting. 3 T MR is also compared to digital radiography for scoring of
ostearthritic changes. With this part of the thesis, it was aimed to confirm that the images obtained with the MR scan of the Small Animal Hospital of the University of Veterinary Medicine Hannover, Foundation, provide an accurate, non-invasive diagnosis of structural changes within the canine knee.
2 Literature review

2.1 Amputation

The amputation of a limb is a commonly performed surgical procedure in small animal practice. It is indicated when there is a permanent and severe loss of limb function, such as severe soft tissue trauma, intractable orthopaedic conditions (mainly bone tumours and severely comminuted fractures) and financial restrictions to afford a specific treatment. Other less common conditions that might lead to an amputation include chronic osteomyelitis, neurological dysfunctions such as sciatic neuropathy or brachial plexus paralysis, congenital limb deformities, vascular disease and arteriovenous fistulas (STONE 1985; LIPOWITZ 1996; WEIGEL 2003). General contraindications of the procedure include severe orthopaedic or neurological disease affecting the remaining limbs and extreme obesity (KIRPENSTEIJN et al. 1999).

In spite of several clinical reports indicating high owner satisfaction after limb amputation in dogs (WITHROW and HIRSCH 1979; CARBERRY and HARVEY 1987; KIRPENSTEIJN et al. 1999; VON WERTHERN et al. 1999), this surgical procedure is still very critically seen by the owners, and even by some veterinarians. Particularly, owners have the tendency to think that the procedure may affect the animals emotionally, as it indeed happens in people (KIRPENSTEIJN et al. 1999; SCHULZ 2009), or that it will be disabling for the animal. Besides, owners are often worried about the possibility of a hypothetic overload of the remaining limbs, which might lead to secondary joint pathologies. Thus, most owners are reluctant to have their dog amputated and many reject the amputation as an alternative to euthanasia or take the decision only after the patient has gone through a painful surgical and/or medical treatment process.

However, the same aforementioned clinical studies in dogs (WITHROW and HIRSCH 1979; CARBERRY and HARVEY 1987; KIRPENSTEIJN et al. 1999; VON WERTHERN et al. 1999) have shown that most owners that were reluctant to have their dogs amputated were satisfied with the overall result. Although some behavioural problems were observed, owners considered that life quality was good.
On the other hand, the fact that the owner is satisfied does not necessarily mean that the amputation does not lead to underlying structural and/or pathologic changes in the animal. In fact, one hypothesis points out that the amputation process might predispose the animal to other orthopaedic conditions; to our knowledge this hypothesis has not been confirmed, refused, or even properly evaluated.

There is one study describing weight redistribution in dogs after an amputation (KIRPENSTEIJN et al. 2000) but there are no studies investigating whether changes in kinematic parameters (such as joint angle progressions and ranges of motion) occur or not. Furthermore, there are no studies evaluating the possible presence of morphologic changes after amputation, such as joint lesions in the remaining limbs. This lack of objective information prevents the veterinarian from providing the owners with accurate information about their concerns; besides, the veterinarian may also have his own concerns. Thus, a hesitating veterinarian might also play a role in deciding against the amputation. Even though the decision of whether to amputate a patient or not is completely up to the owner, the veterinarian is responsible for providing accurate information (WEIGEL 2003), so that the owner can take a decision he will not regret later.

Another important factor to consider is the fact that the few existing studies with amputee patients are retrospective, very likely due to the difficulty to gather enough patients to allow an accurate statistical analysis. This is due to the fact that most amputated animals are oncologic patients (VON WERTHERN et al. 1999) and owners are not always willing to allow additional examinations in a pet that may already be experiencing pain or severe systemic disease. Another important limitation in such studies is the lack of homogeneity of the populations under study. Additionally, in all these studies subjective parameters were used to evaluate the outcome of the animals. As previously mentioned, there is only one previously published report objectively evaluating the gait of amputated dogs (KIRPENSTEIJN et al. 2000). In that study force plate analyses were carried out to measure ground reaction forces (GRF) and contact times for a population of 10 large-breed dogs which had a limb amputated (five forelimbs and five hind limbs). Additionally, the center of gravity was calculated. The
results obtained from the amputated dogs were compared to those from 22 normal dogs of the same weight; it was found that the absence of a limb caused statistically significant changes in the GRF, impulses and contact times of the remaining limbs and the location of the animal’s centre of gravity, in comparison to the control group.

However, there are no prospective studies with animals which need to be amputated, and no study has been done to objectively evaluate kinematics (joint movement) or possible joint changes after a hind limb amputation in dogs. This information is needed in order to properly (and objectively) advise owners about the outcome of an amputation.

2.2 Medial coronoid process disease

Canine elbow dysplasia (CED) is a common disease of young large-breed dogs which may consist of one or more elbow joint disorders, namely medial coronoid process disease (MCPD), ununited anconeal process (UAP), osteochondrosis dissecans of the trochlea humeri (OCD) and joint incongruity (COOK and COOK 2009; TEMWICHITR et al. 2010). The most common condition observed in elbow dysplasia is a MCPD (TEMWICHITR et al. 2010). This disease affects more often large breeds such as Rottweilers, Labrador Retrievers and Bernese Mountain Dogs (TEMWICHITR et al. 2010) but has also been reported in medium-size and mixed-breed dogs (MEYER-LINDENBERG et al. 2002). Young dogs are more prone to the disease; however, it can also occur in older animals (VERMOTE et al. 2010).

For many years, radiography has been the standard for diagnosing CED. However, the presence and severity of MCPD and elbow incongruity can be difficult to diagnose with certainty using this imaging technique alone, due to the complex architecture of the joint and the superimposition of bone structures (REICHLE et al. 2000; COOK and COOK 2009; FITZPATRICK et al. 2009b). In spite of this, there are many radiographic changes associated with MCPD and the secondary arthritis it generates: proximal anconeal osteophytosis, proximal radial osteophytosis and subchondral sclerosis of the semilunar notch and medial coronoid process of the ulna on flexed mediolateral and craniocaudal projections; at the anatomic location of the coronoid process, highly-indicative radiographic findings can be seen (COOK and COOK 2009).
However, for definitive diagnosis of MCPD, other diagnostic modalities may be necessary (REICHLE et al. 2000; COOK and COOK 2009; FITZPATRICK et al. 2009b). Several studies comparing the usefulness of radiography, MR, and surgical findings (SNAPS et al. 1997), computed tomography and arthroscopy (MOORES et al. 2008), and radiography, computed tomography, and arthroscopy (AUMARM 2007) for the diagnosis of elbow dysplasia have been published. Recently, a study comparing the diagnostic value of CT and MR for the diagnosis of a FMCP was published, finding a good correlation between these diagnostic modalities and arthroscopy (KLUMPP et al. 2010). As previously mentioned in the introduction, CT is one of the preferred diagnostic methods to diagnose MCPD. CT scans provide excellent tissue differentiation without superimposition of overlying structures, as it happens with radiography (HATHCOCK and STICKLE 1993; MOORES et al. 2008; COOK and COOK 2009). Nevertheless, cartilage lesions within the joint cannot be evaluated with CT (MOORES et al. 2008); other diagnostic techniques such as MR are needed for this purpose (SNAPS et al. 1997).

Several therapeutic alternatives are possible, including medical management and arthroscopic or surgical removal of the diseased coronoid process (HUIBREGTSE et al. 1994; PUCCIO et al. 2003; TROSTEL et al. 2003; FITZPATRICK et al. 2009a). Arthroscopy is a very popular diagnostic and therapeutic method for a wide range of orthopedic conditions, including cranial cruciate ligament rupture (CCLR), osteochondritis dissecans of the humeral head (OCDH) and fragmentation of the medial coronoid process of the ulna (FMCP) (MARTINI 2003). In one study arthroscopy was found useful to detect and treat the condition even when there are no clear radiographic signs of the disease (MEYER-LINDENBERG et al. 2002). In another study, the same authors described a remarkably better postoperative outcome of the patients treated by arthroscopy, as compared with those treated by arthrotomy (MEYER-LINDENBERG et al. 2003). More recently, a literature review and meta-analysis found that the arthroscopic removal of the MCP is superior to arthrotomy and to medical treatment (EVANS et al. 2008). Besides, arthroscopy is nowadays considered the “gold standard” technique for clinical evaluation of cartilage lesions in the canine elbow (MOORES et al. 2008) and is the method currently used at the Small Animal Hospital of the University of Veterinary Medicine Hannover, Foundation for treating patients suffering from MCPD.
Looking at the role that computerized gait analysis might play in the study of MCPD, it is important to consider that, as opposed to other diseases, such as hip dysplasia and cranial cruciate ligament rupture, there are only few studies that look at gait characteristics in patients with MCPD. In one, joint angular, joint moment and joint power compensations of the shoulder, elbow, carpus and metacarpophalangeal (MCP) joints in dogs with unilateral lameness due to MCPD were evaluated (BURTON et al. 2008). In that study, a quantitative assessment of the effects of elbow dysplasia, specifically fragmented medial coronoid process (FMCP), on thoracic limb mechanics was performed, with the aim to define the adaptive mechanisms affecting gait in dogs with FMCP as well as facilitating an objective comparison of response to different treatment regimes for this disease. The authors suggest that multiple adaptive mechanisms occur in the affected limb in order to compensate the ongoing discomfort. However, there are no studies which prospectively evaluate forelimb kinetics or elbow joint kinematics, osteoarthritis progression or goniometry after the arthroscopic treatment of unilateral MCPD in dogs. Additionally, no controlled comparison has been made in order to determine if functional parameters, such as loads and joint angles, correlate with morphologic parameters. This knowledge is necessary to give the owners a substantiated explanation about what to realistically expect after the arthroscopic treatment of unilateral MCPD in clinical patients.

2.3 Cranial cruciate ligament rupture

One of the most common orthopedic diseases of the dog is the rupture of the cranial cruciate ligament (HAYASHI et al. 2010). This disease commonly results in hind limb lameness, as a result of joint pathologic changes such as osteoarthritis, cartilage erosion and meniscal damage (MOORE and READ 1995; INNES et al. 2000). Due to the complex and multifactorial origin of the disease, preventive strategies have not yet been developed (GRIFFON 2010).

Pathologic changes are commonly seen in the stifle joint of dogs suffering from a cranial cruciate ligament rupture (CCLR), including osteoarthritis, osteophytosis and meniscal tears (D'ANJOU et al. 2008; BÖTTCHER et al. 2010), among others. One of the most clinically relevant lesions, meniscal damage, has been reported to be present in as many as 80% of the
cases (GAMBARDELLA et al. 1981), the medial meniscus being the most commonly affected (LAMPMAN et al. 2003).

Many different surgical techniques have been described to treat the condition. However, none of these can be considered as the gold standard (VAUGHAN 2010), and the technique performed is mainly based on the surgeon's personal preference and experience (KORVICK et al. 1994). Even though new techniques, such as tibial plateau leveling osteotomy (TPLO) and tibial tuberosity advancement (TTA) have been developed, old, "classic" techniques, including the lateral stabilization of the joint (FLO 1975), are still commonly used.

With regard to the diagnosis of joint lesions associated with CCLR, magnetic resonance (MR) imaging is the preferred diagnostic tool to evaluate internal disorders of many joints in people, including the knee (MARINO and LOUGHIN 2010). In humans, MR is commonly used to accurately diagnose certain joint diseases, such as meniscal and ligament tears (CRAWFORD et al. 2007; BLOND et al. 2008; BÖTTCHER et al. 2010). Likewise, in humans suffering from osteoarthritis, MR imaging is the modality of choice to assess the morphology of periarticular soft tissue and articular cartilage (OLIVE et al. 2010). Nevertheless, the usefulness of MR in the context of osteoarthritis, and in general of joint disease, is still not well characterized in veterinary medicine (OLIVE et al. 2010).

Low-field (LF) MR imaging has been found to be valuable in evaluating the appearance of normal and pathologic stifle joints in dogs (BAIRD et al. 1998; KONAR et al. 2005b; WINEGARDNER et al. 2007). However, there are few studies investigating the diagnostic validity of LF MR imaging for the diagnosis of meniscal lesions in dogs with cranial cruciate ligament (CrCL) insufficiency. One of these studies found 0.3 Tesla (T) MR imaging helpful for the diagnosis of complete tears in the canine meniscus, especially in larger dogs, when compared with arthroscopy (MARTIG et al. 2006). Another study, also comparing LF MR imaging with arthroscopy, found a low accuracy of LF MR imaging (0.5 T) to identify meniscal tears (BÖTTCHER et al. 2010).
The introduction of high-field (HF) MR magnets has significantly improved image quality and allowed accurate assessment of subchondral bone lesions, joint spaces, soft tissues, cartilage defects and osteophyte growth in canine knees with experimentally induced osteoarthritis (BOILEAU et al. 2008; D'ANJOU et al. 2008). One study compared the use of 1.5 T MR with computed radiography to assess osteophytosis, subchondral bone sclerosis, joint effusion and soft tissue thickening after experimentally induced osteoarthritis in dogs, finding MR more sensitive than radiography to detect onset and progression of osteophytosis (D'ANJOU et al. 2008). Another study investigated the sensitivity and specificity of 1.5 T MR to detect meniscal tears in clinical cases of CCLR, finding a sensitivity of 100% and a specificity of 94% (BLOND et al. 2008). However, there is no study evaluating 3 T MR images of joint surfaces, cartilage, menisci or ligaments in clinical cases of canine stifle pathology. Ideally, arthroscopy or arthrotomy should be performed, in order to directly visualize the structures of interest, and to be able to accurately assess the results of any diagnostic imaging evaluation, as has been previously described for the stifle (MARTIG et al. 2006; CRAWFORD et al. 2007; BLOND et al. 2008; BÖTTCHER et al. 2010) and the elbow (MOORES et al. 2008) in dogs, and the metacarpus in horses (OLIVE et al. 2010).
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Kinetic, Kinematic, Magnetic Resonance and Owner Evaluation of Dogs Before and After the Amputation of a Hind Limb

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The preliminary results of this study were presented at the 56. Jahreskongress der Deutsche Gesellschaft für Kleintiermedizin on October 22, 2010 in Düsseldorf (Germany).

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3.1 Abstract
This study aimed to prospectively evaluate the recovery outcome of dogs undergoing a hind limb amputation, by investigating how the animal compensates the loss of such limb, using gait (kinetic and kinematic) analyses over a four-month period. Using magnetic resonance (MR) images of the contralateral femorotibial (stifle) joint, the possible presence of morphologic changes in this joint were determined. The subjective impressions of the owner were also gathered and compared with the gait and MR analyses. Twelve patients of different breed, sex and age, in which a hind limb amputation was scheduled, were included. Kinetic data showed that 10 days after the amputation there was redistribution of the load to all remaining limbs, this load shift being more important toward the forelimbs. The recorded kinetic data showed no remarkable changes during the remaining examination time points, indicating that 10 days after the amputation patients had already established their new locomotory pattern. Kinematic data showed significant differences between sessions in the mean angle progression curves of almost all joint angles; however, the ranges of motion (ROMs) of analyzed joints were very similar before and after the amputation and remained constant in the subsequent sessions after the amputation. No changes in the signal intensity of the soft tissues evaluated in the joint were found on the MR evaluation of the contralateral stifle. Besides, no evidence of cartilage damage or osteoarthritis was seen. Finally, owners evaluated the results of the amputation very positively, both during and at the end of the study. It was concluded that dogs have a quick adaptation after a hind limb amputation, and that the adaptation process to the new locomotion begins even before the amputation is performed. This happens without evidence of morphologic changes in the contralateral stifle joint, and with a very positive evaluation from the owner.

Keywords: hind limb amputation, kinetic and kinematic analyses, magnetic resonance imaging, owner evaluation

3.2 Introduction
The amputation of a limb is a commonly performed surgical procedure in small animal practice. Severe trauma and limb tumors are the most common reasons for performing an amputation; other indications include chronic osteomyelitis, neurological dysfunctions such as
sciatic neuropathy and brachial plexus paralysis, congenital limb deformities, vascular disease and arteriovenous fistulas [1-3].

In spite of several clinical reports indicating high owner satisfaction after limb amputation in dogs [4-7], an amputation is still very critically seen by the owners, and even by some veterinarians. Particularly, owners have the tendency to think that the procedure may affect the animals emotionally, as it indeed happens in people [7,8], or that it will be disabling for them. Besides, owners are often worried about the possibility of overload of the remaining limbs, leading to hypothetical secondary joint pathologies. Thus, many owners are reluctant to have their dog amputated, and many reject the amputation as an alternative to euthanasia or take the decision only after the patient has gone through a painful surgical and/or medical treatment process.

The lack of objective information prevents the veterinarian from providing the owners with accurate information about these concerns. A hesitant veterinarian might then play a role in the owner deciding against the amputation. There is only one previously published report objectively evaluating the gait of amputated dogs [9]. In that study, force plate analyses were carried out to measure ground reaction forces (GRF) and contact times in a population of 10 large-breed dogs which had a limb amputation (five forelimbs and five hind limbs). Additionally, the center of gravity was calculated. It was found that the absence of a limb caused statistically significant changes in the GRF, impulses and contact times of the remaining limbs and the location of the animal’s centre of gravity, in comparison to a control group of 22 healthy dogs. However, there are no prospective studies with animals which need to be amputated, and no study has been performed objectively evaluating kinematics (joint movement) or possible joint changes after a hind limb amputation in dogs. This information is needed in order to properly (and objectively) advise owners about the outcome of an amputation.

The general aim of the present study was therefore to prospectively evaluate the gait in dogs before and after amputation of a hind limb, both objectively and subjectively, in order to describe how the animal compensates the loss of a hind limb. Additionally, the stifle of the remaining limb was evaluated for the presence of possible morphologic changes, using magnetic resonance (MR) imaging, due to a hypothetic weight bearing overload of this limb.
The results of this study could be useful for properly advising owners facing the decision to have their dog amputated or not.

3.3 Methods

3.3.1 Objectives

The main objective of the present study was to characterize the recovery outcome of dogs undergoing a hind limb amputation. In order to evaluate the motion and weight bearing characteristics, as well as the duration of adaptation to the three-legged gait, kinematic and kinetic analyses were carried out. Furthermore, magnetic resonance (MR) images of the remaining contralateral femorotibial (stifle) joint were made before and 4 months after the amputation, in order to investigate possible changes in joint morphology. We intended to see if there was a correlation between the functional (kinetic and kinematic gait analysis) and morphologic (MR) characteristics of the stifle joint in the contralateral hind limb. Finally, the subjective impressions of the owner with regard to the recovery of the patient were gathered and compared with the objective results from the gait analysis.

It was hypothesized that there would be marked changes both in the kinetic and the kinematic parameters after the amputation, but that those changes would not impair the ability of the animal to lead a normal life. Based on our clinical experience and some of the aforementioned studies [4-7], it was also hypothesized that there would not be any changes in the contralateral stifle on the MR examination. Thus, after the initial reluctance to the amputation, owners would be satisfied with the procedure.

3.3.2 Patients

All dogs presented at the Small Animal Hospital of the University of Veterinary Medicine Hannover, Foundation (Germany), between March 2010 and October 2011, which needed a hind limb amputation, were included in the study. In total, 12 patients were enrolled. Two additional patients were not included due to aggressiveness in one case, and presence of metallic orthopedic implants in both knees, making it unadvisable to perform the MR, in the other case.
Before surgery a thorough physical examination, including all remaining limbs and the spine, was performed to rule out any disease which might obscure the results. This examination was repeated 10, 30, 90 and 120 days after the amputation. It was planned that, in case an abnormality was suspected, all necessary diagnostic examination tools would be used to determine the type and location of such an abnormality and its possible relationship with the amputation.

3.3.3 Surgical procedure

On the arthroscopy day, all animals were considered good anesthetic candidates (physical status 2 according to the American Society of Anesthesiologists classification system), based on the general clinical examination and blood work. The animals were premedicated using a combination of levomethadone (0.6 mg/kg, L-Polamivet®: Intervet Deutschland GmbH, Unterschleißheim, Germany) and diazepam (0.5 mg/kg, Diazepam-ratiopharm®: Ratiopharm GmbH, Ulm, Germany); anesthesia was induced with propofol dosed to effect (1-4 mg/kg, Narcofol® 10 mg/mL: CP-Pharma Handelsgeellschaft GmbH, Burgdorf, Germany). After orotracheal intubation, anesthesia was maintained with isoflurane (Isofluran CP®: CP-Pharma Handelsgeellschaft GmbH, Burgdorf, Germany) in a 1:1 oxygen:air mixture adjusted according to the clinical signs of anesthetic depth (end-tidal isoflurane 0.7-1.5 vol%) and a continuous rate infusion (CRI) of fentanyl (0.16 µg/kg/min, Fentanyl-Janssen® 0.05 mg/mL: Janssen-Cilag GmbH, Neuss, Germany), lidocaine (50 µg/kg/min, Xylocain® 2%: AstraZeneca GmbH, Wedel, Germany) and ketamine (10 µg/kg/min, Ketamin 10%: Selectavet Dr. Otto Fischer GmbH, Weyarn-Holzolling, Germany). Additionally, a preoperative epidural anesthesia with bupivacaine (0.5 mg/kg, Bupivacain-RPR-actavis® 0.5%: Actavis Deutschland GmbH & Co. KG, Langenfeld, Germany) and morphine (0.1 mg/kg, Morphin Hexal® 10 mg/mL: Hexal AG, Holzkirchen, Germany) and a intraoperative sciatic nerve block with lidocaine (1 mg/kg, Xylocain® 2%, AstraZeneca GmbH, Wedel, Germany) were performed. For postoperative analgesia, carprofen (4 mg/kg, Rimadyl® Injektionslösung: Pfizer GmbH, Berlin, Germany) and the aforementioned CRI of fentanyl, lidocaine and ketamine were used.

The surgical procedure was performed by disarticulation of the hip, as described elsewhere [2]. Depending on their clinical status, the dogs remained in the hospital for approximately 5 days.
3.3.4 Kinetic and kinematic gait evaluation

Kinetic (forces) and kinematic (movement) gait analysis was performed one to three days before the amputation, as well as 10, 30, 90 and 120 days after surgery. Kinetics were measured using a specially designed treadmill (Treadmill model 4060-80: Bertec Corporation, Columbus, OH, USA) consisting of four separate belts, each of them with an integrated force plate underneath. This design allowed the simultaneous measurement of all limb forces. Kinematic analysis was performed with the aid of retro-reflective markers (Ø 16 mm reflective markers: Vicon Motion Systems Ltd., Oxford, UK) positioned on 24 anatomic landmarks (8 per remaining limb), using double-sided adhesive tape; the location of these markers has been previously described [10,11] and is illustrated in Figure 1. Six high-speed infrared cameras (MX3+ camera system: Vicon Motion Systems Ltd., Oxford, UK) were used to record marker movement in all three remaining limbs simultaneously, as the animals were walking at a controlled speed (measurement frequency: 100 Hz). Before each measurement, static and dynamic camera calibration was performed using an L-shaped calibration device (Vicon Calibration Device: Vicon Motion Systems Ltd., Oxford, UK).

On each gait analysis session, patients were gently introduced to the gait on the treadmill; on the first day, a speed at which each individual patient walked comfortably on the treadmill was determined; on each subsequent session the patient was evaluated using the same speed, ranging from 0.5 to 0.8 m/s. During each gait analysis session, two to six trials were recorded, each with a duration of approximately 30 seconds, until at least one valid trial was obtained. A valid trial was defined as 10 consecutive regular steps, in which the dog walked smoothly, without any external forces from the handler being applied, with all paws landing on the appropriate force plate, without overstepping. Video recording was performed, to ensure that the steps were appropriate for analysis.

Both kinetic and kinematic data were simultaneously recorded using commercially available software (Vicon Nexus: Vicon Motion Systems Ltd., Oxford, UK).
Figure 1. Localization of retro-reflective markers and measured angles.
A. Example of the localization of the retro-reflective markers on a healthy patient; B. Illustration of the localization of the retro-reflective markers on the anatomical reference points and the measured angles.
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Ten consecutive steps were afterwards analyzed for the following kinetic parameters: peak vertical force (PFz), mean vertical force (MFz), and vertical impulse (IFz). All forces were normalized to the individual body weight of each dog and data were expressed as percentage of body weight (% BW). Mean ± standard deviation (SD) was calculated from 10 valid consecutive steps. Afterwards, load redistribution (LR) was calculated for each measured parameter (PFz, MFz, IFz) using the following equation (according to Steiss et al. [12]): % load bearing = Fz of the limb/total Fz of all limbs*100. The kinetic data were processed using commercial software (MyoResearch XP Master Edition, Noraxon U.S.A. Inc., Scottsdale, AZ, USA) and exported to a Microsoft® Excel 2007 spreadsheet.

In order to process the kinematic data in Vicon Nexus, all markers were labeled in a trial. Then, 10 valid foot strikes were marked manually to define the gait cycle (stance and swing phases) of each limb. Using a 2-dimensional (2-D) model, projected flexion and extension angles of each remaining joint were calculated: contralateral (with respect to the amputated hind limb) scapulohumeral joint, contralateral cubital joint, contralateral carpal joint, ipsilateral (with respect to the amputated hind limb) scapulohumeral joint, ipsilateral cubital joint, ipsilateral carpal joint, contralateral coxo femoral joint, contralateral femorotibial joint and contralateral tarsal joint. Measured angles are illustrated in Figure 1. In order to compare the movement pattern of each analyzed joint, the gait cycles were normalized to 100 in all dogs and displayed as percentage of one whole stride. The mean joint angle and the range of motion (ROM) of the aforementioned joints were calculated from the mean joint angle progression curves calculated from the 10 strides per dog. The kinematic data were processed using commercial software (Vicon Nexus and Bodybuilder: Vicon Motion Systems Ltd., Oxford, UK) and then exported to a Microsoft® Excel 2007 spreadsheet.

3.3.5 MR evaluation of the contralateral stifle joint

The MR examination was performed under general anesthesia before and 120 days after amputation. The anesthetic protocol was the same described above, excluding local anesthetics and CRIs. Using a state-of-the-art 3 T MR scan (Philips Achieva 3.0T X-series MRI: Philips Healthcare, Hamburg, Germany), images were obtained from the contralateral
knee, with the dog positioned in lateral recumbency; the limb to be examined was in a non-dependent position, with the joint at an angle of ~ 135°. Small (11 cm Ø) surface ring coils (Achieva 3.0T Musculoskeletal SENSE Flex S coil 2 elements) as image enhancers were used, positioned parallel to each other, lateral and medial to the affected knee, and with the joint centered between the two coils. The MR protocol used included a 3-D (3-dimensional) PDW (proton-density weighted) acquisition sequence, which was afterwards reconstructed in sagittal, dorsal and transversal planes, a PDW HR (high-resolution) TSE (turbo spin echo) SENSE (sensitivity encoding for fast MR) sequence in sagittal plane, a PDW HR SPAIR (spectrally adiabatic inversion recovery) SENSE in sagittal plane and a T1-weighted TSE clear (constant level appearance) sequence in sagittal plane (Table 1). This protocol had been previously standardized and considered suitable for performing in clinical cases, as image quality is good and acquisition time is only 20 minutes (total examination time is about 40 minutes including positioning, reference scan, survey, and sequence planning).

Using a high-resolution diagnostic screen (EIZO RadiForce™ RX211 Medical color LCD monitor: Enzo Nanao Corporation, Hakusan, Ishikawa, Japan) the images were assessed by a trained evaluator (VGZ), who looked for changes in the signal intensity of the cranial cruciate ligament (CrCL), the caudal cruciate ligament (CdCL) and the lateral and medial menisci. Possible changes in the cartilage surfaces, as well as evidence of osteoarthritic changes were also evaluated in the lateral and medial femoral condyles, femoral trochlear groove, patella and tibial plateau.

It was expected that, due to a possible underlying metastatic disease, some patients could die or be euthanized before the end of the study; if that was the case, it was planned to ask the owner to authorize the MR examination postmortem.

3.3.6 Owner evaluation of patient comfort

The owner was requested to fill out an evaluation form (modified from Hielm-Björkman et al. [13]) before the amputation and 10, 30, 90 and 120 days after the procedure, in order to gather his/her (subjective) impressions with regard to patient comfort and recovery; these results were compared to those (objective) of the gait analysis.
### Table 1. Magnetic resonance imaging sequences used in this study and their parameters

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Plane</th>
<th>TR</th>
<th>TE</th>
<th>Slice (mm)</th>
<th>Gap (mm)</th>
<th>FOV (mm)</th>
<th>Flip angle</th>
<th>Matrix</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDW</td>
<td>3-D</td>
<td>1300</td>
<td>34</td>
<td>100x100x70</td>
<td>220x167</td>
<td>Joint centered</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PDW</td>
<td>Sagittal</td>
<td></td>
<td>2</td>
<td></td>
<td>90°</td>
<td>True sagittal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PDW</td>
<td>Dorsal</td>
<td></td>
<td>2</td>
<td></td>
<td>90°</td>
<td>Parallel to patella ligament</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PDW</td>
<td>Transverse</td>
<td></td>
<td>2</td>
<td></td>
<td>90°</td>
<td>Parallel to tibial plateau</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PDW HR aTSE SENSE</td>
<td>Sagittal</td>
<td>4326</td>
<td>30</td>
<td>0.2</td>
<td>120x120x48</td>
<td>90°</td>
<td>480x296</td>
<td>True sagittal</td>
<td></td>
</tr>
<tr>
<td>PDW HR SPAIR SENSE</td>
<td>Sagittal</td>
<td>4701</td>
<td>30</td>
<td>0.2</td>
<td>800x800x46</td>
<td>90°</td>
<td>228x160</td>
<td>True sagittal</td>
<td></td>
</tr>
<tr>
<td>T1-weighted TSE clear</td>
<td>Sagittal</td>
<td>665</td>
<td>18</td>
<td>1.8</td>
<td>0.18</td>
<td>90°</td>
<td>180x134</td>
<td>True sagittal</td>
<td></td>
</tr>
</tbody>
</table>

TR: Repetition time; TE: Echo Time; FOV: Field of view; PDW: proton-density weighted; 3-D: 3-dimensional; HR: high resolution; TSE: turbo spin echo; SENSE: sensitivity encoding; SPAIR: spectrally adiabatic inversion recovery; clear: constant level appearance

### Table 2. Patients included in this study

<table>
<thead>
<tr>
<th>Patient</th>
<th>Breed</th>
<th>Sex</th>
<th>Age (Years)</th>
<th>Weight (kg)</th>
<th>Reason to amputate</th>
<th>Gait analyses</th>
<th>Pre</th>
<th>10</th>
<th>30</th>
<th>90</th>
<th>120</th>
<th>PO MR</th>
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<tbody>
<tr>
<td>1</td>
<td>Boxer</td>
<td>Male</td>
<td>8</td>
<td>32</td>
<td>Osteosarcoma</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>2</td>
<td>Labrador</td>
<td>Female</td>
<td>3</td>
<td>31</td>
<td>Rhabdomyosarcoma</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>3</td>
<td>Mixed-breed dog</td>
<td>Female</td>
<td>4</td>
<td>32</td>
<td>Osteosarcoma</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>4</td>
<td>Mixed-breed dog</td>
<td>Male</td>
<td>1</td>
<td>20</td>
<td>Severe soft tissue trauma</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>5</td>
<td>Mixed-breed dog</td>
<td>Male</td>
<td>12</td>
<td>31</td>
<td>Osteosarcoma</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>E</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Swiss Mountain dog</td>
<td>Female</td>
<td>10</td>
<td>39</td>
<td>Osteosarcoma</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>E</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Bernese Mountain dog</td>
<td>Male</td>
<td>2</td>
<td>40</td>
<td>Femoral fracture nonunion</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>8</td>
<td>German Shepherd mix</td>
<td>Male</td>
<td>7</td>
<td>26</td>
<td>Severe soft tissue trauma</td>
<td>+</td>
<td>+</td>
<td>E</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Mixed-breed dog</td>
<td>Female</td>
<td>8</td>
<td>13</td>
<td>Osteosarcoma</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>10</td>
<td>Mixed-breed dog</td>
<td>Female</td>
<td>11</td>
<td>8</td>
<td>Malignant sarcoma</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>11</td>
<td>Landseer</td>
<td>Female</td>
<td>2</td>
<td>54</td>
<td>Fibrosarcoma</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>Mixed-breed dog</td>
<td>Female</td>
<td>8</td>
<td>49</td>
<td>Osteosarcoma</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

PO MR: Postoperative MR scan; +: Performed; -: Not performed; E: Euthanasia
At the end of the study (day 120), owners filled out a questionnaire to assess their final impression regarding the degree of activity and life quality of the dog, and their general impression of and satisfaction with the procedure; besides, owners were encouraged to make further comments. It was planned that if the animal died before the end of the study, an appropriate moment would be looked for to ask the owner to fill out the questionnaire. The questions of the questionnaire were adapted from Carberry and Harvey [4], Withrow and Hirsch [5], von Werthern et al. [6] and Kirpensteijn et al. [7].

3.3.7 Ethics
This study was carried out in accordance with the German Animal Welfare Guidelines and was approved by the Ethics Committee of the Lower Saxony State Office for Consumer Protection and Food Safety (Approval Number: 10A071). Besides, all owners agreed to their pets taking part in the study and signed a consent form.

3.3.8 Statistical methods
Due to the small sample size and very heterogeneous patient population included in this study, it was decided to use non-parametric statistics. Thus, data were analyzed using a Kruskal-Wallis one-way ANOVA test to compare medians between sessions; when statistically significant differences were found, a Wilcoxon signed-rank test for paired observations was performed to determine which session was different. All tests were considered statistically significant if $p<0.05$ and were performed using standard statistical software (GraphPad Prism® Version 4: GraphPad Software, Inc. La Jolla, California, USA). Descriptive statistics were calculated using Microsoft® Excel 2007, where appropriate.

3.4 Results

3.4.1 Clinical data
Breed, sex, age, reason to amputate and performed evaluations of the 12 patients enrolled in this study are illustrated in Table 2. As can be seen in this table, the most common reason for performing the amputation was a tumor, followed by trauma and one surgical complication. Six right and six left hind limbs were amputated. Patient 8 died unexpectedly soon after the amputation due to abdominal bleeding caused by a previously asymptomatic hepatic hemangiosarcoma. Nine patients survived until the end of the study.
Patient 12 presented bilateral hip osteoarthritis; however, it was asymptomatic, and no clinical signs (pain, lameness, difficulty standing up, etc.) were detected before or after the amputation. All other patients showed no abnormalities in the clinical examination of the remaining limbs. No patient showed spine abnormalities throughout the study.

3.4.2 Kinetic and kinematic gait evaluation

The results of the kinetic and kinematic evaluations are presented in Figures 2 to 5 and Tables 3 and 4. It is important to note that, although nine patients survived until the last examination day, the kinetic and kinematic data were not available from all of them: even though all patients were capable of walking unaided to the gait analysis laboratory (see supplementary video 2), once on the treadmill some of the animals refused to walk: Patient 7 simply lay down on the treadmill, and was finally enrolled only for performing the MR examinations and gathering the owners’ assessments. Patient 4 refused to walk on the treadmill before amputation; however, during the next sessions he walked perfectly, with valid trials. Other patients walked intermittently in such a way that the trials were not valid for analysis, even when they had previously walked perfectly on the treadmill. Moreover, although all owners were extremely cooperative, some were at times reluctant to allow their pets to be walked on the treadmill long enough to record valid trials.

Kinetic data showed that 10 days after amputation there was redistribution of the load to all remaining limbs, this load shift being more important towards the forelimbs (Figure 2 and Table 3). The values and pattern of load shifting are represented in Figure 2. The recorded PFz, MFz and IFz values showed no remarkable changes during the remaining examination time points, indicating that 10 days after the amputation the patient had already reached its new locomotory pattern. This was true for all patients including the lightest (8 kg) and the heaviest (54 kg) ones. Very interestingly, there were no statistically-significant differences between sessions (Table 3). With regard to the kinematic gait analysis, even though the patients walked smoothly on the treadmill (see supplementary video 1), there were significant differences between sessions in the means of almost all joint angles (Table 4). It is important to note that there were also important variations within a patient in the same session (not
shown in Table 4). The mean joint angle progression curves showed a similar pattern between sessions (Figures 3 to 5), but they had huge individual variations (not shown).

**Figure 2.** Illustration of the load redistribution (LR).

LR averages for the A. peak (PFz); B. mean (MFz); and C. integral (IFz) values. The values in the bars indicate the mean % body weight (BW) loaded by each limb for each calculated parameter.
Table 3. Results of the kinetic analysis

<table>
<thead>
<tr>
<th></th>
<th>Pre</th>
<th>10</th>
<th>30</th>
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<th>120</th>
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**PFz contralateral forelimb**

<table>
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<th></th>
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<th>SD</th>
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<tbody>
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<td>n = 11</td>
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<td>n = 10</td>
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<tr>
<td>n = 8</td>
<td>69.78</td>
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<tr>
<td>n = 8</td>
<td>66.74</td>
<td>8.27</td>
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</table>

**PFz ipsilateral forelimb**

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<td>67.78</td>
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<td>n = 11</td>
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**PFz contralateral hind limb**

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**PFz contralateral hind limb**

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<td>n = 8</td>
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**MFz contralateral forelimb**

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<td>6.93</td>
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<tr>
<td>n = 11</td>
<td>50.27</td>
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**MFz contralateral hind limb**

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<td>n = 8</td>
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**MFz contralateral hind limb**

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<td>n = 11</td>
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<td>9.10</td>
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<td>8.45</td>
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<tr>
<td>n = 8</td>
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**IFz contralateral hind limb**

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<td>n = 8</td>
<td>21.51</td>
<td>5.23</td>
</tr>
<tr>
<td>n = 8</td>
<td>23.21</td>
<td>7.62</td>
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</table>

$p$: p value of the Kruskal-Wallis test; PFz: Peak vertical forces; MFz: Mean values of the vertical forces; IFz: Integral of the vertical forces; SD: Standard deviation
Figure 3. Joint angle progression curves of each measured angle in the contralateral forelimb. Note the similarity of the curves before and after amputation.
Figure 4. Joint angle progression curves of each measured angle in the ipsilateral forelimb. Note the similarity of the curves before and after amputation.
Figure 5. Joint angle progression curves of each measured angle in the contralateral hind limb. Note the similarity of the curves before and after amputation.
Table 4. Results of the kinematic analysis

<table>
<thead>
<tr>
<th>Joint</th>
<th>Pre (n=9)</th>
<th>10 (n=10)</th>
<th>30 (n=9)</th>
<th>90 (n=7)</th>
<th>120 (n=6)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contralateral scapulohumeral joint</td>
<td>Mean ± SD 115.2 ± 5.67</td>
<td>117.9 ± 5.83</td>
<td>115.4 ± 5.54</td>
<td>112.7 ± 6.09</td>
<td>112.3 ± 4.24</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>ROM ± SD 27.68 ± 7.48</td>
<td>31.46 ± 8.12</td>
<td>29.51 ± 6.73</td>
<td>31.49 ± 6.26</td>
<td>26.07 ± 6.04</td>
<td>0.4784</td>
</tr>
<tr>
<td>Contralateral cubital joint</td>
<td>Mean ± SD 114.9 ± 12.93</td>
<td>115.9 ± 12.82</td>
<td>126.5 ± 11.59</td>
<td>127.2 ± 13.67</td>
<td>123.6 ± 13.91</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>ROM ± SD 57.98 ± 15.56</td>
<td>61.8 ± 11.64</td>
<td>56.51 ± 14.74</td>
<td>60.75 ± 13.06</td>
<td>62.74 ± 9.60</td>
<td>0.8981</td>
</tr>
<tr>
<td>Contralateral carpal joint</td>
<td>Mean ± SD 192.2 ± 26.85</td>
<td>191.5 ± 24.89</td>
<td>190.1 ± 26.03</td>
<td>191.5 ± 25.66</td>
<td>185.8 ± 26.88</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>ROM ± SD 99.38 ± 19.62</td>
<td>97.45 ± 11.28</td>
<td>104.7 ± 10.83</td>
<td>94.25 ± 13.65</td>
<td>101.1 ± 8.17</td>
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<tr>
<td>Ipsilaterial scapulohumeral joint</td>
<td>Mean ± SD 117.5 ± 7.92</td>
<td>120.1 ± 8.33</td>
<td>111.9 ± 6.87</td>
<td>112.4 ± 6.94</td>
<td>112.1 ± 7.12</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>ROM ± SD 34.11 ± 5.69</td>
<td>32.2 ± 4.35</td>
<td>29.77 ± 4.80</td>
<td>32.17 ± 2.71</td>
<td>31.06 ± 5.03</td>
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</tr>
<tr>
<td>Ipsilaterial cubital joint</td>
<td>Mean ± SD 114.6 ± 12.28</td>
<td>117.6 ± 13.33</td>
<td>116.7 ± 12.94</td>
<td>121.5 ± 13.63</td>
<td>123.8 ± 13.58</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>ROM ± SD 55 ± 11.81</td>
<td>57.96 ± 11.92</td>
<td>57.23 ± 12.69</td>
<td>59.84 ± 12.73</td>
<td>57.78 ± 11.82</td>
<td>0.9168</td>
</tr>
<tr>
<td>Ipsilaterial carpal joint</td>
<td>Mean ± SD 185.5 ± 26.36</td>
<td>185.6 ± 24.54</td>
<td>190.6 ± 25.54</td>
<td>185.9 ± 23.23</td>
<td>185.5 ± 26.05</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>ROM ± SD 92.65 ± 19.14</td>
<td>91.83 ± 18.76</td>
<td>91.01 ± 15.71</td>
<td>82.42 ± 12.51</td>
<td>93.36 ± 10.05</td>
<td>0.6301</td>
</tr>
<tr>
<td>Contralateral coxofemoral joint</td>
<td>Mean ± SD 116.1 ± 8.37</td>
<td>118.4 ± 6.96</td>
<td>120.8 ± 7.516</td>
<td>116.8 ± 6.29</td>
<td>116.1 ± 6.64</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>ROM ± SD 30.25 ± 6.22</td>
<td>27.47 ± 9.90</td>
<td>30.08 ± 9.71</td>
<td>25.17 ± 9.09</td>
<td>24.89 ± 6.27</td>
<td>0.5011</td>
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<tr>
<td>Contralateral femorotibial joint</td>
<td>Mean ± SD 123.2 ± 7.48</td>
<td>115.8 ± 6.62</td>
<td>110.4 ± 5.76</td>
<td>114.7 ± 5.55</td>
<td>113.3 ± 5.68</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>ROM ± SD 42.4 ± 4.28</td>
<td>37.67 ± 8.44</td>
<td>37.82 ± 7.34</td>
<td>40.8 ± 12.16</td>
<td>34.83 ± 8.31</td>
<td>0.2990</td>
</tr>
<tr>
<td>Contralateral tarsal joint</td>
<td>Mean ± SD 130.5 ± 8.98</td>
<td>121 ± 10.93</td>
<td>117.8 ± 14.07</td>
<td>124.9 ± 12.21</td>
<td>127.2 ± 10.75</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>ROM ± SD 47.74 ± 10.2</td>
<td>50.57 ± 10.52</td>
<td>61.27 ± 14.25</td>
<td>57.73 ± 11.24</td>
<td>48.04 ± 14.17</td>
<td>0.1432</td>
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</tbody>
</table>

Mean: mean joint angle calculated from the mean joint angle progression curves; SD: Standard deviation; ROM = Range of Motion; p = p value of the Kruskal-Wallis test
Despite all these different kinematic results, ROMs of all analyzed joints were very similar before and after amputation and remained constant in the subsequent sessions after the amputation, without significant differences between sessions (Table 4).

3.4.3 MR evaluation of the contralateral stifle joint

Postoperative MR examination was possible only in eight patients. Although nine patients survived until the end of the study, severe metastatic disease was detected in patient 11 on day 120, and the MR examination was not performed. Postmortem MR examination was not possible in any case. No changes in the signal intensity of the CrCL, CdCL or the lateral and medial menisci were found, in comparison with the preoperative MR images. No changes in the cartilage surface, and no evidence of osteoarthritic changes were found (Figure 6).

![Figure 6. Examples of MR images (sequence: PDW Vista Spair, sagittal plane).](A. before and B. 120 days after amputation. No changes could be detected in the joint 120 days after the procedure.)

3.4.4 Owner evaluation of patient comfort

The owners’ assessment of patient comfort and the final questionnaire were made in German and translated into English as accurately as possible. The results of the owners’ assessment of
patient comfort are presented in table 5 and show a clear tendency of the patients to improve after amputation. The patient numbers were entered in this Table, in order to enable the reader to see the individual outcome of each animal. Ten owners answered the final questionnaire: nine from patients surviving until the end of the study and one from a patient which died the very same day of the final examination (Patient 6). This questionnaire revealed a high degree of owner satisfaction with the amputation result: Eight owners were very satisfied with the results of the amputation and two were satisfied; none were dissatisfied. Seven owners considered that the dog had adapted very well to the amputation, two that it had adapted well, and one that it had a fair outcome; none considered the outcome as poor. Seven owners considered that the dog took less time than expected to recover, three that recovery time was as expected and none considered that recovery took longer than expected. Seven owners responded that no behavioral changes had occurred and three gave affirmative answers: “now the dog is afraid of going upstairs, downstairs is no problem”, “when walking outside, the dog gets tired more easily” and one owner did not give any reason. Most (eight) owners were prevented from allowing the amputation to be performed: they feared that the animal could not move after the amputation and lead a normal life (4 cases), fear of the procedure itself (1 case), fear of behavioral changes (2 cases) and fear of a decrease in life quality (1 case). All owners would take the decision to amputate again, in case it is required in another dog. Two owners considered that the degree of activity after the amputation increased, six that it remained the same, and only two that it had decreased, although an owner stated that this was “minimal”. Seven owners considered that the life quality of the patient increased after the amputation, four that it remained the same and none considered that it had decreased. Additional comments included: “we have not regretted the decision to amputate the dog for a second”, “we are happy we made the decision to have the dog amputated”, “I would advise other owners to allow the amputation. The need for amputation is no reason to euthanize a dog. The dog runs just as before surgery”, “The dog stands up without any difficulty”. Especially remarkable were the comments of the owners of patient 6 (died just before the last session) “Thanks to the amputation we could enjoy the company of our dog for a few additional months. She was free of pain” and of patient 12 (bilateral hip osteoarthritis) “Thanks for offering us the possibility to have our dog amputated. It was the right decision”.
<table>
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<th>Attitude</th>
<th>Pre</th>
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<th>30</th>
<th>90</th>
<th>120</th>
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<td>3,5</td>
<td>2,4,5,6,11,12</td>
<td>2,7,10,11</td>
<td>2,7,11</td>
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<tr>
<td>Alert</td>
<td>1,9,10,11,12</td>
<td>1,2,4,7,8,10,11,12</td>
<td>1,3,7,9,10</td>
<td>1,3,4,6,9,12</td>
<td>1,3,4,6,9,10,12</td>
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<td>6,9</td>
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<td>Ø</td>
<td>Ø</td>
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<td>Ø</td>
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<tr>
<td>Depressed</td>
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<td>Ø</td>
<td>Ø</td>
<td>Ø</td>
<td>Ø</td>
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<td>Willingness to move (general)</td>
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<td></td>
<td></td>
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<td>Very willing</td>
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<td>4,5,7</td>
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<td>2,3,6,7,10</td>
<td>2,4,7,10,12</td>
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<tr>
<td>Willing</td>
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<td>1,2,3,6,8,10,11,12</td>
<td>1,2,9,10,11</td>
<td>6,9,11,12</td>
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<tr>
<td>Hesitant</td>
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<td>9</td>
<td>Ø</td>
<td>1</td>
<td>Ø</td>
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<tr>
<td>Reluctant</td>
<td>12</td>
<td>Ø</td>
<td>Ø</td>
<td>Ø</td>
<td>Ø</td>
</tr>
<tr>
<td>Does not move</td>
<td>4</td>
<td>Ø</td>
<td>Ø</td>
<td>Ø</td>
<td>Ø</td>
</tr>
</tbody>
</table>

The dog ...

... lies down ...

Easily | 7,8,10 | 5,7,10,12 | 3,5,6,7,10,11,12 | 1,2,3,4,7,9,10,11,12 | 1,2,3,4,6,7,10,12 |
Carefully | 1,3,6,9,11 | 1,2,3,4,6,8,9 | 1,2,4,9 | 6 | 11 |
Slowly | 2 | 11 | Ø | Ø | Ø |
with difficulty | 4,5 | Ø | Ø | Ø | Ø |
with a lot of difficulty | 12 | Ø | Ø | Ø | Ø |
... stands up ...

Easily | 7,8,9,10 | 7,10 | 6,7,10,12 | 3,4,7,9,10 | 3,4,7,10,12 |
Carefully | 1,3,5 | 1,2,3,4,5,6,8,9,11,12 | 1,3,4,5,9,11 | 1,2,6,11 | 1,6 |
Slowly | 6,11 | Ø | 2 | 12 | 2,11 |
with difficulty | 2,4 | Ø | Ø | Ø | Ø |
with a lot of difficulty | 12 | Ø | Ø | Ø | Ø |

* Modified from Hielm-Björkman et al. [13]; Ø: None of the owners marked this option
Table 5. Owner assessment of patient comfort* (continued)

<table>
<thead>
<tr>
<th>Willingness to move after resting</th>
<th>Very willing</th>
<th>Willing</th>
<th>Hesitant</th>
<th>Reluctant</th>
<th>Does not move</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ø</td>
<td>3,7,9,10,11,11</td>
<td>1,2,3,4,6,10,11</td>
<td>1,3,5,9,11,12</td>
<td>2,6,9,11,12</td>
</tr>
<tr>
<td></td>
<td>Ø</td>
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<th>Willing</th>
<th>Hesitant</th>
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<td>§</td>
<td>5,12</td>
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* Modified from Hielm-Björkman et al. [13]; Ø: None of the owners marked this option
3.5 Discussion

This study was performed in order to characterize the recovery outcome of dogs undergoing a hind limb amputation, both objectively and subjectively. We intended to evaluate the motion and weight bearing characteristics, as well as the time to reach the adjustments needed to cope with the three-legged gait, using kinetic and kinematic analyses. Additionally, possible changes in stifle joint morphology were evaluated and the subjective impressions of the owner with regard to the recovery of the patient were gathered and compared with the objective results from the gait analysis. The main goal was to provide owners and veterinarians with accurate, objective information, not existing previously, about the outcome of the amputation (i.e. how the dog adapted to the new locomotory status) and find out if the owners' fears were founded.

No impairing changes occurred after the amputation: the kinetic and kinematic analyses revealed that the patients had begun adapting to the new locomotory situation even before the amputation was performed, and that 10 days after the procedure, all significant changes had already taken place. The MR examination found no changes in the contralateral remaining stifle joint within four months after amputation. Besides, the owners soon realized that their fears about the negative consequences of the amputation were unfounded.

Examination times were chosen due to the fact that in a previous study, in which owners of canine amputees were interviewed [7] most dogs adapted to the amputation within a month, some within a week, and all within 3 months after surgery. With the last follow-up 120 days after the procedure, a final attempt was made to find any evidence of further gait changes. Since there is the belief that orthopedic disease might occur in the remaining limb after amputation, as a result of a theoretical overload, the contralateral stifle was morphologically assessed using MR images, to evaluate this likelihood. The stifle was chosen, instead of the coxofemoral or tarsal joint, as the former has been extensively investigated, and there is a whole body of literature exemplifying normal and pathologic MR images to compare [14-19].

Just as expected, a very heterogeneous population was found in this study: different breeds, ages and weights. The main reason for amputating a patient was the presence of a tumor,
which agrees with previous studies [6,7]. The mortality seen in this study was related to the metastatic process and not to the amputation itself.

No clinical abnormalities on examination of the remaining limbs or the spine, which could indicate a deleterious effect of the procedure, were found after amputation. Even the patient suffering from hip osteoarthritis (12) had a positive outcome, and the owner was very satisfied with her decision.

With regard to the kinetic and kinematic evaluations, it is unfortunate that it was not possible to perform all examinations on all patients. However, exclusively using “good” trials allowed us to obtain reliable results. It should be noted that, even though a valid trial implied that the handler did not exert any external forces, it was not possible to have the animals completely free on the treadmill (see supplementary video 1). The kinetic data showed a quick adaptation of the patient to the new locomotory situation after amputation. It is remarkable that the largest patient (patient 11 - 54 kg) and the smallest one (patient 10 – 8 kg) adapted equally well. These results agree with the study of Kirpensteijn et al. [7], indicating that the subjective observations made by the owners of such study were more accurate than expected. The present study has the advantage of looking at the patients objectively and prospectively, leaving no doubt about the fast adaptation of all animals. The fact that there were no significant changes in the load redistribution after amputation was initially surprising; however, it is easily explainable: all patients were severely lame before the amputation, meaning that the adaptation and compensation to the lack of a hind limb had begun to take place before the amputation was performed. This was even clearer when looking only at those patients which did not load the affected limb at all before surgery.

The kinematic results (including the statistical analysis) should be interpreted with caution. The fact that significant differences were found in the absolute values of the different joint angles could be explained by the normal variation inherent to motion analysis: marker localization changes lead to changes in joint angles measured. Even though every effort was made to place the markers in the right position, small variations might have occurred, leading to different measurements. However, also huge variations were seen within a session (not
shown in Table 4 or Figures 3 to 5), possibly indicating that the patients adapted to every step they make and in a very irregular manner. This could be explained by the fact that several gait patterns are possible at a given speed and by a permanent adjustment of the speed of the animal to the treadmill speed [20]. It should also be taken into account that slow speeds were used before the amputation, in order to avoid worsening the pain that patients were already experiencing. After the amputation the animals could have walked on the treadmill more comfortably at faster speeds (personal observations). Even though this might have caused an irregular walking pattern after the procedure, speeds were kept constant to avoid adding a variance factor when measuring the GRF [21]. Finally, the angles measured here can be used to illustrate the movement patterns for the patients in this study, and they cannot be extrapolated to other patient populations. However, our study focuses on determining whether there are variations in the different kinematic parameters before and after amputation in this particular patient population, and that does not seem to be the case.

The similarity in the ROMs before and after surgery is a remarkable finding. The measurement of ROMs seems to be less susceptible to the sources of error commonly found in kinematic studies (misplacement of markers and skin movement), at least in the hind limb [22]. Therefore, the results of the ROMs are more accurate than the absolute measurement of joint angles. That being said, the lack of significant differences between sessions suggests that the patient had also begun to adapt to the new movement situation before amputation, and that this remained stable after the procedure.

With regard to the MR examination, no changes in the remaining contralateral knee were found after amputation; this could indicate that an overload in the remaining contralateral hind limb, leading to joint pathology, is not very likely. It was decided to investigate this point, as it is commonly believed by the general public, and even by some veterinarians, that amputating a dog might predispose it to orthopedic abnormalities; the results of our MR (and also our clinical examinations) proved otherwise, at least for the stifle. Although 4 months after amputation might possibly be a short time to evaluate joint changes, a previous study describing the experimentally induced rupture of the CrCL in 5 crossbred dogs showed that it is possible to see changes in the cartilage and subchondral bone as early as 4 weeks after the
rupture [17]. It is of course difficult to extrapolate such findings to this study, but it could indicate that, if there were ongoing changes in joint morphology, they would be visible 4 months after amputation. Besides, most of our research subjects were oncologic patients, with a (likely) short life span. Measuring cartilage thickness would have been a more accurate method to evaluate subtle joint changes [17]. Unfortunately, this could not be done due to software limitations.

With regard to the owner evaluation assessment of the patient after the procedure, the results were as expected: in Table 5, the positive outcome of most patients can be clearly seen. The improvement is especially remarkable in the ability of the dog to lie down and stand up. The lack of improvement or worsening of some parameters for patients 1, 2 and 11, seemed to be related more to the declining general condition of the patient, than to the effects of the amputation itself.

The responses to the final questionnaire were also as expected: most owners were initially reluctant to have their dogs amputated, but were satisfied with the overall result and the quality of life was considered good; this is in agreement with other studies [4-7]. In the present study, some owners even considered that their pet’s quality of life improved after the amputation, and this might have been related to the removal of the source of pain. The behavioral changes reported by the owners in this study were more small disabilities than behavioral problems. The behavioral problems previously reported [7], such as aggression and anxiety, were not seen in the patients of the present study.

As in previous studies [4,7], all owners responded that they would have another pet amputated, and none regretted their decision. Even the owner who had just lost his pet at the end of the evaluation period of four months had only positive comments about the amputation. With regard to the evaluation of the other oncologic patients, which died shortly after the procedure, we believe this evaluation would have been negatively biased, as the owners could have given a bad evaluation to a patient that is, for instance recumbent, due to the systemic process and not to the amputation itself.
The favorable responses of most owners are easily explainable, as they are in agreement with the results of the gait analysis and the MR imaging.

3.5.1 Limitations

There were important limitations in this study: the lack of a homogeneous population prevented us from comparing the kinetic and kinematic data with other studies looking at normal patient populations or using a control group. However, it is virtually impossible to perform such a clinical study using a homogeneous population. Besides, kinematic data are breed-specific [23], and not all breeds have been studied yet. In any case, in the present study there were a high number of mixed-breed dogs, which are very difficult to characterize.

3.5.2 Conclusions

It can be concluded that, in spite of the limitations, this study provides convincing and objective evidence, indicating that dogs have a quick adaptation process after a hind limb amputation, at least up to four months after the procedure. The adaptative processes to the new locomotion begin even before the amputation is performed. Since the veterinarian is responsible for providing accurate information before an amputation [2], we strongly believe that this study provides useful information that will allow veterinarians the possibility to give dog owners more realistic expectations after a hind limb amputation.

3.6 Competing interests

The authors declare that they have no competing interests.

3.7 Supporting information

Video 1: Thirty-two kilogram patient walking on the treadmill at 0.8 m/s. Although the walking pattern is very similar between sessions, evident differences can be observed.

Video 2: Forty-kilogram dog (patient 7) walking and running 4 months after the amputation. Note that the dog has no difficulty in its movements whatsoever, neither when walking nor when running.

3.8 Acknowledgements

The authors acknowledge the cooperation of Alexa Jötzke, Sabine Kramer, Verena Nerschbach, Stefanie Schmidt, Julia Tünsmeyer and Linda Ungemach, who were involved in
the medical, anesthetic or surgical management of the patients used in this study. As well, we wish to thank Peter Dziallas, Beate Länger and Davina Wolf for performing the MRs, Martin Beyerbach for his statistical assistance and the patients’ owners for their cooperation.

3.9 Author contributions
Conceived the study: IN. Designed the study: VGZ VvB NE DB IN PW. Performed data collection: VGZ, VvB, NE. Analyzed the data: VGZ PW. Wrote the paper: VGZ. Critical revision of the manuscript: VGZ VvB NE DB IN PW. Final approval of the version to be published: VGZ VvB NE DB IN PW.

3.10 References


4. Manuscript II

Evaluation of forelimb loads along with elbow movement and morphology in dogs before and after the arthroscopic management of unilateral medial coronoid process disease

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Partially supported by the National University of Colombia and the Colombian government in cooperation with the German Academic Exchange Service (DAAD) by a research scholarship awarded to VGZ.

This study was performed at the Small Animal Hospital, University of Veterinary Medicine Hannover, Foundation. Bünteweg 9, D-30559 Hannover, Germany.
The preliminary results of this study were presented at the 57. Jahreskongress der Deustche Gesellschaft für Kleintiermedizin on November 11, 2011 in Berlin (Germany) and the 4th Graduate School Day of the Hannover Graduate School for Veterinary Pathobiology, Neuroinfectology, and Translational Medicine on November 26, 2011 in Bad Salzdetfurth (Germany).

The authors declare that no competing interests exist.
4.1 Abstract

**Objective:** To evaluate forelimb loads and symmetry, together with elbow function and morphology before and after the arthroscopic treatment of unilateral medial coronoid process disease (MCPD) in clinical patients. Additionally, to determine if functional parameters correlate with morphologic findings.

**Study Design:** Prospective case series.

**Sample Population:** Dogs (n=14) with forelimb lameness.

**Methods:** Patients were included when lameness was confirmed as being caused by unilateral MCPD. Kinetic analysis of both forelimbs, along with kinematic analysis and goniometry of both elbows were carried out before and 60, 120 and 180 days after partial coronoidectomy performed by arthroscopy. Radiography and computed tomography of both elbows were also performed before and 180 days after the arthroscopy.

**Results:** A non-significant ($p=0.1093$) increase in the loads applied by the affected limb was seen. There were highly significant differences in the mean loading forces between forelimbs in all sessions. Symmetry index improved, with significant differences between sessions ($p=0.0190$). However, kinematic parameters showed no significant differences, neither between sessions nor when comparing both elbows within sessions. Goniometry revealed no significant differences between sessions, but some were found when comparing both elbows within sessions. Osteophytosis and degree of lameness showed no correlation, neither before ($r_s=-0.07683; p=0.7940$) nor after arthroscopy ($r_s=0.2700; p=0.3505$).

**Conclusions:** Only the kinetic parameters improved after arthroscopy, without full restoration of function. Kinematic parameters showed no improvement. Osteoarthritis and goniometric
measurements in the affected joint worsened. Functional parameters did not correlate with morphologic findings.

**Clinical relevance:** Partial coronoidectomy only leads to partial recovery of limb function.

**Keywords:** medial coronoid process disease, arthroscopy, kinetics, kinematics, goniometry, osteoarthritis

### 4.2 Introduction

Medial coronoid process disease (MCPD) is the most common condition associated with canine elbow dysplasia (CED),¹ which often causes forelimb lameness in dogs.² Although large breeds are more commonly affected, MCPD has also been reported in medium-sized and mixed-breed dogs.³ Young dogs are more prone to the disease; however, it is also present in older animals.⁴

Radiography has been the classical method of choice to rule out MCPD, since it is readily available in most veterinary practices, inexpensive and easy to perform.⁵,⁶ However, radiography is more useful for assessing the associated radiographic changes, than for accurately observing the medial coronoid process (MCP) itself.²,⁵,⁶ More recently, computed tomography (CT) has become one of the preferred diagnostic methods for diagnosing MCPD: CT allows multislice, multidirectional cross-sectional imaging, alleviating the problem of bone superimposition associated with radiography.⁷,⁸

Several alternatives are possible for treating MCPD, including medical management and arthroscopic or surgical removal of the diseased MCP.²,⁹⁻¹¹ A study found arthroscopy useful for detecting and treating the condition even when there were no clear radiographic signs of the disease.³ In another study, the same authors described a remarkably better postoperative
outcome in those patients treated by arthroscopy, when compared with those treated by arthrotomy.\textsuperscript{12} More recently, a literature review and meta-analysis found that the arthroscopic removal of the MCP is superior to arthrotomy and to medical treatment.\textsuperscript{13} Even though these studies were performed using subjective methods to evaluate patient recovery, the arthroscopic treatment of MCPD is nowadays regarded as the preferred diagnostic and therapeutic approach for the treatment of this condition.\textsuperscript{12}

However, recent studies performed using objective methods of gait analysis (inverse dynamics\textsuperscript{14} and peak vertical forces, vertical impulse and goniometry\textsuperscript{15}) concluded that arthroscopy is not superior to medical treatment\textsuperscript{14} or to arthrotomy\textsuperscript{15} for treating MCPD, refuting the results of the aforementioned studies. Therefore, the arthroscopic treatment of MCPD might be overestimated.

To the authors’ knowledge, there are no studies which prospectively evaluate forelimb kinetics or elbow joint kinematics, osteoarthritis progression or goniometry after arthroscopic treatment of unilateral MCPD in dogs. Thus, the objective of this prospective study was to objectively evaluate forelimb load as well as elbow function and morphology, before and after arthroscopic treatment of unilateral MCPD in clinical patients, to analyze the progression of the recovery. Additionally, we aimed to determine whether the functional parameters (kinetic and kinematic gait analysis, and goniometry) correlate with the morphologic (radiography) parameters.

\textbf{4.3 Materials and Methods}

This study was carried out in accordance with the German Animal Welfare Guidelines and was approved by the Ethics Committee of the Lower Saxony State Office for Consumer
Protection and Food Safety (Approval Number: 10A072). Besides, all owners agreed to their pet’s participation in the study and signed a consent form.

4.3.1 Patients
Between August 2010 and September 2011, all patients suspected of suffering exclusively from unilateral MCPD disease (i.e. unilateral forelimb lameness, pain during clinical examination of the elbow, and radiographic changes suggesting the condition [sclerosis of the trochlear notch and/or changes in contour at the level of the MCP]), scheduled for arthroscopy, were included. A thorough orthopedic and radiographic examination was carried out, in order to rule out any concomitant orthopedic disease, either within the joint (concomitant ununited anconeal process, osteochondritis dissecans and/or elbow incongruity) or elsewhere in the locomotor system. In total, 20 patients were enrolled. The orthopedic examination was again performed on the day of the arthroscopy, as well as 60, 120 and 180 days after the procedure.

4.3.2 Arthroscopy
On the arthroscopy day, all animals were considered good anesthetic candidates (physical status 1 or 2 according to the American Society of Anesthesiologists classification system), based on the general clinical examination and blood work. The animals were premedicated using a combination of acepromazine (0.05 mg/kg, Vetranquil® 1%: Albrecht GmbH, Aulendorf, Germany), given intramuscularly 20-30 minutes before the induction, and levomethadone (0.6 mg/kg, L-Polamivet®: Intervet Deutschland GmbH, Unterschleißheim, Germany) administered immediately before inducing the patient; anesthesia was induced with propofol dosed to effect (1-4 mg/kg, Narcofol® 10 mg/mL: CP-Pharma Handelsgesellschaft GmbH, Burgdorf, Germany). After orotracheal
intubation, anesthesia was maintained with isoflurane (Isofluran CP®: CP-Pharma Handelsgesellschaft GmbH, Burgdorf, Germany) in a 1:1 oxygen:air mixture adjusted according to the clinical signs of anesthetic depth (end-tidal isoflurane 0.7-1.5 vol%). For postoperative analgesia, carprofen (4 mg/kg, Rimadyl® Kautablette: Pfizer GmbH, Berlin, Germany) was used for 10 days.

The arthroscopy was performed through medial portals, as described elsewhere,\textsuperscript{12} using a commercially available arthroscope (2.4 mm short 25-degree oblique arthroscope: Richard Wolf GmbH Germany, Knittlingen, Germany) and video system (Telecam® 20210030/PAL: KARL STORZ GmbH & Co. KG, Tuttlingen, Germany). The presence of one or more of the following changes confirmed the MCPD:\textsuperscript{16} presence of a fissure at the level of the medial coronoid process, presence of a fragment at the level of the medial coronoid process, deformation of the medial coronoid process. Once the MCPD had been confirmed, a partial coronoidectomy was carried out, using a previously described technique.\textsuperscript{12} After the procedure, the animals received standard medical care and remained in the clinic until fully recovered. All patients were released from the clinic the same day.

4.3.3 Kinetic and kinematic gait evaluation

Kinetic and kinematic gait analyses were performed one to three days before the arthroscopy, as well as 60, 120 and 180 days after the procedure. Both kinetic and kinematic data were simultaneously recorded using commercially available software (Vicon Nexus: Vicon Motion Systems Ltd., Oxford, UK). Ground reaction forces were measured using a specially designed treadmill (Treadmill model 4060-80: Bertec Corporation, Columbus, OH, USA) consisting of four separate belts, each of them with an integrated force plate underneath. This design allowed the simultaneous measurement of ground reaction forces of all four limbs separately.
Analysis of elbow joint kinematics was made with the aid of retro-reflective markers (Ø 16 mm reflective markers: Vicon Motion Systems Ltd., Oxford, UK) positioned using double-sided adhesive tape. The markers were located at the greater tubercle of the humerus, lateral epicondyle of the humerus and ulnar styloid process, as previously described. Six high-speed infrared cameras (MX3+ camera system: Vicon Motion Systems Ltd., Oxford, UK; measurement frequency: 100 Hz) were used to record marker movement in both elbows simultaneously. Before each measurement, static and dynamic camera calibration was performed using an L-shaped calibration device (Vicon Calibration Device: Vicon Motion Systems Ltd., Oxford, UK). On admission, patients were gently introduced to the treadmill and a speed at which each individual patient walked comfortably was determined. This speed ranged from 0.65 to 1.1 m/s. The same speeds were used for the subsequent sessions. Two to six trials, each lasting approximately 30 seconds, until at least one valid trial was obtained, were recorded in each session. A valid trial was defined as 10 consecutive regular steps in which the dog walked smoothly, without any external forces from the handler being applied, with all paws landing on the appropriate force plate, without overstepping. Video recordings were made to ensure that the steps were appropriate for analysis.

Ten consecutive steps were analyzed afterwards to calculate the peak vertical forces (PFz) of each forelimb, which were normalized to the individual body weight of each dog and expressed as a percentage of body weight (% BW). Mean ± standard deviation (SD) was calculated from 10 valid consecutive steps. Afterwards, a symmetry index (SI) was calculated for the PFz using the following equation: SI = ([X_A - X_H]/([X_A + X_H]*0.5))*100, with X representing the mean PFz value of the affected (A) and the normal (H) limbs from the ten steps. Placing the affected side on the left side of the formula results in a negative SI when the dog remains lame; a positive value indicates that the formerly affected limb loads more than
the normal one; and a value of 0 indicates perfect symmetry. A patient was considered not lame if the SI < 5%. In order to calculate the correlation between the degree of lameness (i.e. between the SI), and the degree of osteoarthritis, a scoring of the SI (symmetry index score - SIS) was made: < 5% = score 0, 5-9.9% = score 1, 10-14.9% = score 2 and > 15% = score 3. The kinetic data were processed using commercial software (MyoResearch XP Master Edition, Noraxon U.S.A. Inc., Scottsdale, AZ, USA) and exported to a Microsoft® Excel 2007 spreadsheet.

In order to process the kinematic data, all markers were labeled in a trial. Then, 10 valid foot strikes were marked manually in order to define the gait cycle (stance and swing phases) of each forelimb. Using a 2-dimensional model, projected flexion and extension angles of each elbow joint were calculated (normal and affected elbow), as previously described. In order to compare the movement pattern of each analyzed elbow joint, the gait cycles were normalized to 100 in all dogs and displayed as a percentage of one whole stride. Maximal extension and flexion angles, as well as the range of motion (ROM) of both elbow joints were calculated from the mean joint angle progression curves calculated from the 10 strides per dog. The kinematic data were processed using commercial software (Vicon Nexus and Bodybuilder: Vicon Motion Systems Ltd., Oxford, UK) and then exported to a Microsoft® Excel 2007 spreadsheet.

4.3.4 Goniometric evaluation of the elbow joints
Maximal extension and flexion angles, as well as ROM of both elbow joints were determined one to three days before and 60, 120 and 180 days after arthroscopy, using a commercially-
available plastic goniometer (Goniometer model 47: PRESTIGE® Medical, Northridge CA, USA), and previously described methodology.\textsuperscript{21}

4.3.5 Radiographic and computed tomographic evaluation of the elbow joints

The radiographic and computed tomographic examinations were performed under general anesthesia 1-3 days before and 180 days after arthroscopy. The anesthetic protocol was the same as described above. For the radiographic examination, digital radiographs (BuckyDiagnost and Philips Optimus 80: Philips Medical Systems DMC GmbH, Hamburg, Germany) of both elbows were made. In order to accurately assess all possible elbow disorders, four projections were evaluated:\textsuperscript{8} neutral mediolateral, flexed mediolateral, craniocaudal, and craniolateral-15°-caudomedial oblique. Using a high-resolution diagnostic screen (EIZO RadiForce\textsuperscript{TM} RX211 Medical color LCD monitor: Enzo Nanao Corporation, Hakusan, Ishikawa, Japan), the images were scored by a trained evaluator (VGZ), and osteoarthritis was graded according to Table 1.\textsuperscript{6,7,22}

<table>
<thead>
<tr>
<th>Osteophyte Score (OS)</th>
<th>Definition</th>
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<tbody>
<tr>
<td>0 (none)</td>
<td>No osteophytes present</td>
</tr>
<tr>
<td>1 (mild)</td>
<td>Osteophytes &lt; 2 mm present</td>
</tr>
<tr>
<td>2 (moderate)</td>
<td>Osteophytes 2-5 mm present</td>
</tr>
<tr>
<td>3 (severe)</td>
<td>Osteophytes &gt; 5 mm present</td>
</tr>
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</table>

The evaluator was unaware as to which patient or session (pre or postoperative) the radiographs belonged. CT images were obtained from both elbow joints, using a state-of-the-art 64-channel CT scan (Philips Brilliance 64 CT Scanner: Philips Healthcare, Hamburg, Germany), as previously described.\textsuperscript{8}
Two evaluators (VGZ and PD, or VGZ and DCW) assessed the CT images using a diagnostic workstation (Philips Brilliance Workspace Portal V2: Philips Healthcare, Hamburg, Germany) to confirm the presence of unilateral MCPD.

### 4.3.6 Statistical methods
Due to the small sample size and very heterogeneous patient population included in this study, it was decided to use non-parametric statistics. Thus, data were analyzed using a Kruskal-Wallis one-way ANOVA test to compare medians between sessions. When statistically significant differences were found, a Wilcoxon signed-rank test for paired observations was performed to determine which session was different. A Spearman’s rank correlation coefficient was calculated to determine the correlation between the osteophyte score (OS) and the degree of lameness. All tests were considered statistically significant if $p<0.05$ and were performed using standard statistical software (GraphPad Prism® Version 4: GraphPad Software, Inc. La Jolla, California, USA). Descriptive statistics were calculated using Microsoft® Excel 2007, where appropriate.

### 4.4 Results

#### 4.4.1 Patients
Initially, 20 patients were enrolled in the present study. However, three patients were excluded due to presence of bilateral MCPD, as detected on the CT images. Two additional patients had no MCPD: in one case the patient was positive to *Anaplasma phagocytophilum*; in another case, the cause of lameness could not be found. Finally, one patient was lost to follow-up, and was excluded from data analysis. Thus, 14 patients are reported in this study. Breeds included four mixed-breed dogs, four Labrador Retrievers, and one Golden Retriever, Rottweiler, Polish Lowland Sheepdog, German Wirehaired Pointer, Belgian Malinois and
Irish Setter. There were five females and nine males, with a mean age of 5.09 years (range 10 months–12 years) and mean weight of 28.4 kg (range 16–37 kg). Six left elbows and eight right elbows were affected. Twelve patients were clinically free of lameness and one patient showed mild lameness at the end of the study (patient 12). A second arthroscopy was performed on patient 4 after the third gait analysis session (120 days after surgery) due to unsatisfactory recovery. Therefore, the kinetic, kinematic and goniometric data of the last session (180 days after arthroscopy) of this patient were missing, and the radiographic and computed tomographic data collected prior to the second arthroscopy (obtained 120 days after the procedure) were available and used to calculate the postoperative OS and SIS.

4.4.2 Kinetic and kinematic gait evaluation

With regard to the kinetic gait analysis, the PFz of both forelimbs (expressed as % BW) was calculated, and a comparison between the normal and the affected side is shown in Figure 1. A progressive increase in the loads applied by the affected limb was evident. However, differences between sessions did not reach statistical significance (p=0.1093). A slight increase in the loading forces on the normal side was also seen, with no significant differences between sessions (p=0.8446). When comparing the normal vs. affected side, there were highly significant differences in the mean loading forces in all sessions, including the last one (Table 2). The SI illustrated in Figure 2 shows the high variability in the degree of lameness between patients before arthroscopy (SI: -12.95), and the recovery afterwards, being especially noticeable 180 days after the procedure (SI: -3.84%), which is similar to the PFz results. However, in this case there were statistically significant differences between sessions (p=0.0190), the last session being the only one which was different to the others (Table 2).
Figure 1. Comparison of the peak vertical forces (% BW) of the affected and the normal forelimbs before and after arthroscopy, including standard deviation bars. Note that significant differences between limbs were present throughout the whole study.

Figure 2. Symmetry index measured before and after arthroscopy, including standard deviation bars. Note the high variability in the degree of lameness, especially before arthroscopy.
### Table 2. p values of the kinetic and kinematic parameters measured in this study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Comparison</th>
<th>Session</th>
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<tbody>
<tr>
<td>Peak vertical forces (PFz)</td>
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</tr>
<tr>
<td>Affected side</td>
<td>All sessions</td>
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<td>0.1093</td>
</tr>
<tr>
<td>Normal side</td>
<td>All sessions</td>
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<td>0.8446</td>
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<td>Normal vs. affected side pre</td>
<td>pre</td>
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<td>0.0001</td>
</tr>
<tr>
<td>Normal vs. affected side 60</td>
<td>60</td>
<td></td>
<td>0.0004</td>
</tr>
<tr>
<td>Normal vs. affected side 120</td>
<td>120</td>
<td></td>
<td>0.0009</td>
</tr>
<tr>
<td>Normal vs. affected side 180</td>
<td>180</td>
<td></td>
<td>0.0061</td>
</tr>
<tr>
<td>Symmetry index (SI)</td>
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<tr>
<td>Both sides</td>
<td>All sessions</td>
<td></td>
<td>0.0190</td>
</tr>
<tr>
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<td></td>
<td>0.2166</td>
</tr>
<tr>
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<td>pre</td>
<td></td>
<td>0.1353</td>
</tr>
<tr>
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<td></td>
<td>0.6698</td>
</tr>
<tr>
<td>Both sides 60 vs. 180</td>
<td>60</td>
<td></td>
<td>0.0398</td>
</tr>
<tr>
<td>Both sides 120 vs. 180</td>
<td>120</td>
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<td>0.0398</td>
</tr>
<tr>
<td>Maximal extension angle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
<td>0.9329</td>
</tr>
<tr>
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<td>All sessions</td>
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<td>0.4275</td>
</tr>
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<td>pre</td>
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<td>60</td>
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</tr>
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<td></td>
<td>1.0000</td>
</tr>
<tr>
<td>Maximal flexion angle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Affected side</td>
<td>All sessions</td>
<td></td>
<td>0.8395</td>
</tr>
<tr>
<td>Normal side</td>
<td>All sessions</td>
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<td>0.5837</td>
</tr>
<tr>
<td>Normal vs. affected side pre</td>
<td>pre</td>
<td></td>
<td>0.2163</td>
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<td>Normal vs. affected side 60</td>
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<td></td>
<td>0.6848</td>
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<tr>
<td>Normal vs. affected side 120</td>
<td>120</td>
<td></td>
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<tr>
<td>Normal vs. affected side 180</td>
<td>180</td>
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<td>0.2734</td>
</tr>
<tr>
<td>Range of Motion (ROM)</td>
<td></td>
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<td>Affected side</td>
<td>All sessions</td>
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<td>Normal side</td>
<td>All sessions</td>
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<td>0.9219</td>
</tr>
<tr>
<td>Normal vs. affected side pre</td>
<td>pre</td>
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<td>0.4143</td>
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<tr>
<td>Normal vs. affected side 60</td>
<td>60</td>
<td></td>
<td>0.1909</td>
</tr>
<tr>
<td>Normal vs. affected side 120</td>
<td>120</td>
<td></td>
<td>0.0803</td>
</tr>
<tr>
<td>Normal vs. affected side 180</td>
<td>180</td>
<td></td>
<td>0.0681</td>
</tr>
</tbody>
</table>
The SI illustrated in Figure 2 shows the high variability in the degree of lameness between patients before arthroscopy (SI: -12.95), and the recovery afterwards, being especially noticeable 180 days after the procedure (SI: -3.84%), which is similar to the PFz results. However, in this case there were statistically significant differences between sessions (p=0.0190), the last session being the only one which was different to the others (Table 2).

The kinematic gait analysis showed no statistically significant differences when comparing maximal extension angle, maximal flexion angle and ROM of both the normal and affected side, neither between nor within sessions (Table 2). The maximal extension and flexion angles were very similar when comparing the normal and affected sides (Figure 3A and B, respectively). The ROMs showed very little variation between sessions and, even though there were no statistically significant differences between sessions or limbs (Table 2), they were constantly decreased in the affected joint, when compared with the normal side (Figure 3C).

**4.4.3 Goniometric evaluation of the elbow joints**

Regarding the goniometric data, some results were similar to those of the kinematic gait analysis: there were no statistically significant differences when comparing maximal extension angle, maximal flexion angle and ROM of both normal and affected side, when comparing between sessions (Table 3). However, maximal extension angles (last session only), maximal flexion angles (all sessions) and ROMs (all sessions, except before the arthroscopy) were significantly different when comparing normal vs. affected side within sessions (Table 3). The absolute values of the maximal extension angles were very similar when comparing these of the normal and the affected side in all sessions (Figure 4A). In
contrast, maximal flexion angles were significantly higher in the affected side than in the normal side in all sessions (Figure 4B).

**Figure 3.** Maximal extension angles (A), maximal flexion angles (B) and range of motion (C) of the affected and normal forelimbs before and after arthroscopy, including standard deviation bars, measured by kinematic analysis. Note the similarity between limbs and sessions (A and B), and the constantly decreased ROMs of the affected side, compared to the normal side (C).
Table 3. *p* values of the goniometric parameters measured in this study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Comparison</th>
<th>Session</th>
<th><em>P</em> value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximal extension angle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Affected side</td>
<td>All sessions</td>
<td></td>
<td>0.9790</td>
</tr>
<tr>
<td>Normal side</td>
<td>All sessions</td>
<td></td>
<td>0.2774</td>
</tr>
<tr>
<td>Normal vs. affected side</td>
<td>pre</td>
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</tr>
<tr>
<td>Normal vs. affected side</td>
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<td>Normal vs. affected side</td>
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<tr>
<td>Normal vs. affected side</td>
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<td>0.0059</td>
</tr>
<tr>
<td>Maximal flexion angle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Affected side</td>
<td>All sessions</td>
<td></td>
<td>0.6374</td>
</tr>
<tr>
<td>Normal side</td>
<td>All sessions</td>
<td></td>
<td>0.2511</td>
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<tr>
<td>Normal vs. affected side</td>
<td>pre</td>
<td></td>
<td>0.0479</td>
</tr>
<tr>
<td>Normal vs. affected side</td>
<td>60</td>
<td></td>
<td>0.0024</td>
</tr>
<tr>
<td>Normal vs. affected side</td>
<td>120</td>
<td></td>
<td>0.0034</td>
</tr>
<tr>
<td>Normal vs. affected side</td>
<td>180</td>
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<td>0.0002</td>
</tr>
<tr>
<td>Range of Motion (ROM)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Affected side</td>
<td>All sessions</td>
<td></td>
<td>0.8283</td>
</tr>
<tr>
<td>Normal side</td>
<td>All sessions</td>
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<td>0.0803</td>
</tr>
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</tr>
<tr>
<td>Normal vs. affected side</td>
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<td>0.0005</td>
</tr>
<tr>
<td>Normal vs. affected side</td>
<td>180</td>
<td></td>
<td>0.0002</td>
</tr>
</tbody>
</table>

The goniometry ROMs showed very little variation between sessions and, very similar to the results of the kinematic ROMs, they were constantly lower in the affected side than in the normal side (Figure 4C). However, both maximal flexion angles and ROMs showed progressively more evident statistical differences between the normal and the affected side as time elapsed (Table 3).
Figure 4. Maximal extension angles (A), maximal flexion angles (B) and range of motion (C) of the affected and normal forelimbs before and after arthroscopy, including standard deviation bars, measured by goniometry. Note the similarity between limbs and sessions (A), and the constantly increased flexion angles (B) and constantly decreased ROMs (C) of the affected side, compared to the normal side, which were especially noticeable in the last session.
4.4.4 Radiographic and computed tomographic evaluation of the elbow joints

Different degrees of osteophytosis were found in the radiographic evaluation of the affected joints before arthroscopy, including eight patients which showed no signs of osteoarthritis (Table 4). However, all affected elbow joints showed an increase in the degree of osteoarthritis at the end of the study (Table 4 and Figures 5A, 5B and 6A). All contralateral normal joints remained free of disease, as confirmed by the radiographic and CT examinations performed at the end of the study (Figure 6B).

There was no correlation between the OS and the degree of lameness (SIS, Table 4), neither before (r_s=-0.07683 [95% confidence interval: -0.5951 to 0.4866]; p=0.7940) nor after arthroscopy (r_s=0.2700 [95% confidence interval: -0.3201 to 0.7091]; p=0.3505). Seven patients were still lame at the end of the study (SIS > 0) and the only patient which showed an increase in the SIS after arthroscopy (patient 12) was the same which clinically showed a mild lameness at the end of the study (Table 4).

The CT evaluation performed before arthroscopy confirmed the presence of unilateral MCPD (Figure 6A left and 6B left). The second CT evaluation, performed 180 days after arthroscopy, confirmed the removal of the diseased MCP (Figure 6A right) and that the normal joint remained free of MCPD (Figure 6B right).
Figure 5. Radiographic images of the elbow joint of a patient before (left) and 180 days after (right) arthroscopy in cranial-caudal (A) and medial-lateral (B) views. An increase in the presence and size of osteophytes after arthroscopy (indicating worsening of osteoarthritis) is evident.
Figure 6. Computed tomographic images (coronal view) of the elbow joint of a patient before (left) and 180 days (right) after arthroscopy. The presence of MCPD (arrow) before arthroscopy (A-left) and the removal of the diseased MCP (A-right) after arthroscopy were confirmed. The absence of MCPD and lack of osteoarthritic changes in the normal elbow throughout the study were also confirmed (B).
Table 4. Osteophyte and symmetry index scores for each patient before (pre) and 180 days (post) arthroscopy

<table>
<thead>
<tr>
<th>Patient</th>
<th>Osteophyte score (OS)</th>
<th>Symmetry index score (SIS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
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<td>2</td>
</tr>
<tr>
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<td>2</td>
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<td>2</td>
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<td>6</td>
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<td>1</td>
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<tr>
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<td>1</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>14</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

SIS: SI<5%=score 0; SI 5-9.9%=score 1; SI 10-14.9%=score 2; SI>15%=score 3

4.5 Discussion

One fourth of the patients had to be excluded from the study due to misdiagnosis of unilateral MCPD: three patients suffered from bilateral MCPD, even though there were only unilateral signs. This has been previously described. Two additional patients presented clinical signs resembling unilateral MCPD, but were suffering from another orthopedic disease, which in one case could not be diagnosed. In all these cases, the CT images were definitive for making a correct diagnosis of unilateral MCPD. An additional patient lost to follow-up is a common situation in prospective studies.

Many different breeds are represented in this study, including mixed-breed dogs. There was only one patient younger than one year (10 months old). In contrast to previous reports, the patient population was represented almost exclusively by adult animals in the present study. However, a high incidence of MCPD in dogs > 18 months old has been reported.
Besides, many older dogs are present in this study (seven patients older than six years), which is in agreement with a previous study reporting a relatively high incidence of MCPD in dogs older than 6 years.\textsuperscript{4}

Only one patient had an unsatisfactory follow-up (persistent lameness), which led to a second arthroscopy of the same joint before completing the study. All other patients made a satisfactory clinical recovery, with only one of them showing a mild lameness at the end of the study.

Comparisons between sessions were made, in order to see the progression of the lameness as time elapsed, and within sessions to compare the normal with the affected limb. PFz were used to make the comparisons, since they are the most accurate.\textsuperscript{20} The lack of significant differences in the increase of the PFz of the affected limb between sessions indicates that the functional recovery was not impressive. More importantly, the finding of significant differences in the PFz between the normal and the affected limb in all sessions, including the last one, indicates that during the 6-month period of evaluation, most patients did not reach complete restoration of limb function. Although these results are somewhat surprising, a previous study using total support moment ratios to evaluate the symmetry of the forelimbs indicates that patients may need more than 12 months to fully recover after a partial coronoidectomy performed by arthroscopy.\textsuperscript{21} The very slight increase in the PFz of the normal forelimb might be part of the compensatory mechanisms involved in a forelimb lameness. However, in the present study we did not attempt to see how weight redistribution occurred. Instead, we wanted to assess patient recovery, and the symmetry index and peak forces comparison between the limbs of the same girdle were previously used for this purpose.\textsuperscript{19,24-26}
Looking at the symmetry index, it seems clear that the recovery of many patients began after the third session (120 days after arthroscopy), and that many did not fully recover from the lameness at the end of the study: seven patients were completely free of lameness (i.e. SI < 5%), but six patients recovered only partially, and one patient’s worsened (Table 4). As previously mentioned, these results are in accordance with those of the PFz analysis, and indicate that many patients need more than 180 days to fully recover.

With regard to the kinematic gait analysis, the lack of significant differences in the maximal extension and flexion angles, as well as in the ROM, is remarkable. This was observed both between sessions, when looking at each limb, and within sessions, when comparing normal vs. affected limb. These results indicate that neither the lameness nor the increase in the PFz or the decrease in the SI (both indicating lameness recovery) reflect important changes in the kinematic parameters. However, as time elapsed, ROM significance values (normal vs. affected side) progressively decreased, almost reaching significance (Table 2). It is possible that, if this study had lasted longer, a significant decrease in the ROM in the affected side would have been found after a few additional months. A decrease in the ROM and an increase in the maximal flexion angle (both indicating less joint mobility) in the affected elbow is an expected result due to the increase in the OS, and agrees with the results of the goniometry. A previous study looking at different physical therapy exercise regimes in patients with elbow osteoarthritis, found that the affected joints had an increased ROM and decreased maximum flexion angle (i.e. the affected joints had more mobility) during a specific exercise, which is contrary to our results. Even though those findings were interpreted as a possible
compensation mechanism, in that report six of ten studied patients presented bilateral elbow osteoarthritis, and the authors acknowledged that the interpretation of the results was difficult.

The fact that the maximal extension and flexion angles and the ROM measured by goniometry did not differ between sessions, this being very similar to the kinematic results, indicates that there were in fact few changes in the ability of the affected joint to move, as time elapsed. However, when comparing normal vs. affected side within sessions, goniometry seemed to reflect more accurately the changes happening in the joint: an increased maximal flexion angle and a decreased ROM indicate that the affected elbows had in fact passive mobility impairment. In spite of this, the ability of the joint to move actively during locomotion was not affected (see kinematic analysis above), which may explain why, even though OS worsened, the animals were able to recover from the lameness.

All affected elbow joints showed an increase in the OS. This is remarkable, specially taking into consideration the fact that eight patients showed no signs of osteoarthritis before arthroscopy. Although this is an expected result, based on previous studies, it is disappointing to find that the coronoidectomy does not prevent, and apparently does not slow down, osteoarthritic development.

When looking at the OS and the SIS, it is clear that there was no correlation between the morphologic and functional findings. This is in agreement with other previous studies, and possibly indicates that the lameness was a direct result of the inflammatory process caused by the pathologic coronoid process within the joint, and not the result of the osteoarthritis as such.
Finally, the CT evaluation of both elbow joints before and after arthroscopy was made to confirm that the MCPD was present only in one elbow, and to confirm that the contralateral elbow remained unchanged. In order to be able to make a correct interpretation of the kinetic, kinematic and goniometric data of the affected joint, it was essential that the contralateral elbow remained unaltered throughout the study. The diagnosis of MCPD was made using CT, as it is a reliable imaging method, even in cases where there are no evident radiographic changes indicating the presence of MCPD. On the other hand, the diagnosis of MCPD using only radiographs is difficult.

4.5.1 Limitations
The lack of a homogeneous population prevented us from comparing the kinetic and kinematic data with other studies looking at normal patient populations. Besides, kinematic data are breed-specific, and not all breeds have been characterized, yet. The great heterogeneity of our patients also led to a huge data variability. With regard to the radiographic evaluation of osteoarthritis, the assessments were performed by a single observer. Although this person was unaware as to which patient or session (pre or postoperative) the radiographs belonged, he was aware that he was assessing only the patients included in this study, which could have biased the evaluation.

4.5.2 Conclusions
The arthroscopic intervention of medial coronoid process disease led to functional improvement of the kinetic parameters only, without full restoration of function; the kinematic parameters showed no improvement. Morphologically (degree of osteoarthritis) and mechanically (goniometry), there was a worsening of the affected joint. Thus, this study
indicates that the arthroscopic treatment of MCPD is of limited benefit. Even though there are some previous studies reporting similar results,\textsuperscript{10,14} this is the first study which looks simultaneously at several objective functional and morphologic parameters to quantify the outcome of actual patients after the arthroscopic treatment of unilateral MCPD. More studies comparing different treatment modalities, which look at objective, measurable parameters, and are performed in a larger patient population, are needed to further evaluate these findings.

4.6 Acknowledgements
The authors acknowledge the cooperation of Drs. Alexandra Becker, Verena von Babo, Ricarda Dening, Prof. Andrea Meyer-Lindenberg, Mirja Nolff and Julia Tünsmeyer, who were involved in the medical, anesthetic or arthroscopic management of the patients used in this study. As well, we wish to thank Drs. Christiane Henjes and Beate Länger for performing some of the CTs, Dr. Martin Beyerbach for his statistical assistance and the patients’ owners for their cooperation.

4.7 References


5. Manuscript III

Diagnostic validity of 3 Tesla magnetic resonance imaging and digital radiographs for diagnosing stifle joint lesions in dogs with cranial cruciate ligament rupture

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5.1. Abstract

Background
Magnetic resonance (MR) imaging is the preferred diagnostic tool to evaluate internal disorders of many joints in humans, including the stifle; however, the usefulness of MR imaging in the context of osteoarthritis, and in general of joint disease, is yet to be characterized in veterinary medicine. The objective of this study was to assess the diagnostic accuracy of 3 Tesla MR imaging when evaluating cranial and caudal cruciate ligament, meniscal and cartilage damage, as well as degree of osteoarthritis, in dogs affected by naturally-occurring cranial cruciate ligament rupture (CCLR). Osteoarthritis scoring was also performed using digital radiographic images. Twenty-one client-owned dogs were included in this study. One experienced evaluator assessed all the images, and the results were compared with the actual surgical findings observed during arthrotomy.

Results
All cranial cruciate ligaments were correctly identified as ruptured. With one exception, all caudal cruciate ligaments were correctly identified as non-ruptured. High sensitivities and specificities were obtained when diagnosing meniscal rupture. Additional lesions could be observed, both in the cranial and caudal cruciate ligaments and in the menisci; however, their clinical significance is yet to be determined. There was a clear agreement between the MR and radiographic findings with the surgical findings, with regard to the parameters cartilage damage and degree of osteoarthritis. MR imaging was not superior to radiography for the assessment of osteoarthritis.

Conclusions
Presence of cruciate ligament damage, meniscal rupture and degree of osteoarthritis could be properly assessed on the MR. However, in the case of meniscal evaluation, some margin for misdiagnosis is still present.

Keywords: dog, stifle, cranial cruciate ligament, high-field MRI, radiography
5.2 Background

Pathologic changes are commonly seen in the stifle joint of dogs suffering from a cranial cruciate ligament rupture (CCLR), including osteoarthritis, osteophytosis and meniscal tears [1, 2], among others. The accurate diagnosis of such changes is cornerstone for deciding adequate therapy, being particularly useful to avoid unnecessary surgical explorations when performing procedures such as tibial plateau leveling osteotomy (TPLO) or tibial tuberosity advancement (TTA), in which the procedure itself does require opening the joint. Besides, a more accurate prognosis can be given to the owner.

In humans, magnetic resonance (MR) is the preferred diagnostic method to assess periarticular soft tissue and articular cartilage, as well as to evaluate stifle lesions such as meniscal and ligament tears [2-6]. In spite of this, the usefulness of MR in the context of osteoarthritis, and in general of joint disease, is still not well characterized in veterinary medicine [6].

Low-field (LF) MR imaging has been found to be valuable in evaluating the appearance of normal and pathologic stifle joints in dogs [7-9]. However, there are few studies investigating the diagnostic validity of LF MR imaging for the diagnosis of meniscal lesions in dogs with cranial cruciate ligament (CrCL) insufficiency. One of these studies found 0.3 Tesla (T) MR imaging helpful for the diagnosis of complete tears in the canine meniscus, especially in larger dogs, when compared with arthroscopy [10]. Another study, also comparing LF MR imaging with arthroscopy, found a low accuracy of LF MR imaging (0.5 T) to identify meniscal tears [2].

The introduction of high-field (HF) MR magnets has significantly improved image quality and allowed accurate assessment of subchondral bone lesions, joint spaces, soft tissues, cartilage defects and osteophyte growth in canine stifles with experimentally-induced osteoarthritis [1, 11]. One study compared the use of 1.5 T MR with computed radiography to assess osteophytosis, subchondral bone sclerosis, joint effusion and soft tissue thickening after experimentally-induced osteoarthritis in dogs, finding MR more sensitive than radiography to detect onset and progression of osteophytosis [1]. Another study investigated the sensitivity and specificity of 1.5 T MR to detect meniscal tears in clinical cases of CCLR, finding a sensitivity of 100% and a specificity of 94% [3]. However, to the authors’ knowledge, there is no study evaluating 3 T HF MR imaging in clinical cases of canine stifle pathology.
The objective of this study was to determine the agreement between 3 T MR images and the actual surgical findings, with regard to the diagnosis of joint lesions associated with a CCLR in dogs, using a short-duration MR protocol. 3 T MR is also compared to digital radiography for scoring of osteoarthritic changes. It was hypothesized that the images obtained with our MR scan would provide an accurate, non-invasive diagnosis of structural changes within the canine stifle, which should highly correlate with the surgical findings.

5.3 Materials and Methods

Twenty-one dogs presented at the Small Animal Hospital of the University of Veterinary Medicine Hannover, Foundation (Germany), which were diagnosed as having CCLR (by means of the cranial drawer test, the tibial compression test and stifle radiographs) were included in this study. The study was carried out in accordance with the animal welfare guidelines of the State of Lower Saxony. No ethical approval was obtained, as the MR and radiographic examinations were part of the diagnostic database of each patient; however, all owners agreed to their pet’s participation in the study and signed a consent form. All animals were considered good anesthetic candidates (physical status 2 according to the American Society of Anesthesiologists classification system), based on the general clinical examination and blood work. On the examination day, the animals were anesthetized using a combination of acepromazine\(^a\) (0.05 mg/kg), levomethadone\(^b\) (0.6 mg/kg), propofol\(^c\) (1-5 mg/kg) and isoflurane\(^d\) in oxygen (1-2.5%); for additional intra and post-operative analgesia carprofen\(^e\) (4 mg/kg) was given. Once under anesthesia, the animals were moved to the MR suite. Using a state-of-the-art 3 T MR scan\(^f\), images were obtained from the affected stifle, with the dog positioned in lateral recumbency; the limb to be examined was in a non-dependent position, with the joint at an angle of ~ 135\(^\circ\). Small (11 cm Ø) surface ring coils\(^g\) as image enhancers were used, positioned parallel to each other, lateral and medial to the affected stifle, and with the joint centered between the two coils.

The MR protocol used included a 3-D (3-dimensional) PDW (proton-density weighted) acquisition sequence, which was afterwards reconstructed in sagittal, dorsal and transversal planes, a PDW HR (high-resolution) TSE (turbo spin echo) SENSE (sensitivity encoding for fast MR) sequence in sagittal and dorsal planes, a PDW HR SPAIR (spectrally adiabatic inversion recovery) SENSE in sagittal plane and a T1-weighted TSE clear (constant level appearance) sequence in sagittal plane (Table 1).
### Table 1. Magnetic resonance imaging sequences used in this study and their parameters

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Plane</th>
<th>TR</th>
<th>TE</th>
<th>Slice (mm)</th>
<th>Gap (mm)</th>
<th>FOV (mm)</th>
<th>Flip angle</th>
<th>Matrix</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDW</td>
<td>3-D</td>
<td>1300</td>
<td>34</td>
<td>100x100x70</td>
<td></td>
<td>220x167</td>
<td></td>
<td>Joint centered</td>
<td></td>
</tr>
<tr>
<td>PDW</td>
<td>Sagittal</td>
<td>2</td>
<td>90°</td>
<td></td>
<td></td>
<td>90°</td>
<td></td>
<td>True sagittal</td>
<td></td>
</tr>
<tr>
<td>PDW</td>
<td>Dorsal</td>
<td>2</td>
<td>90°</td>
<td></td>
<td>2 0.2</td>
<td>120x120x48</td>
<td>90°</td>
<td>True sagittal</td>
<td>Parallel to patella ligament</td>
</tr>
<tr>
<td>PDW</td>
<td>Transverse</td>
<td>2</td>
<td>90°</td>
<td></td>
<td></td>
<td>344x235</td>
<td></td>
<td>Parallel to tibial plateau</td>
<td></td>
</tr>
<tr>
<td>PDW HR aTSE SENSE</td>
<td>Sagittal</td>
<td>4326</td>
<td>30</td>
<td>2</td>
<td>0.2</td>
<td>120x120x48</td>
<td>90°</td>
<td>480x296</td>
<td>True sagittal</td>
</tr>
<tr>
<td>PDW HR aTSE SENSE</td>
<td>Dorsal</td>
<td>4324</td>
<td>30</td>
<td>2</td>
<td>0.2</td>
<td>120x120x48</td>
<td>90°</td>
<td>344x235</td>
<td>Parallel to patella ligament</td>
</tr>
<tr>
<td>PDW HR SPAIR SENSE</td>
<td>Sagittal</td>
<td>4701</td>
<td>30</td>
<td>2</td>
<td>0.2</td>
<td>800x800x46</td>
<td>90°</td>
<td>228x160</td>
<td>True sagittal</td>
</tr>
<tr>
<td>T1-weighted TSE clear</td>
<td>Sagittal</td>
<td>665</td>
<td>18</td>
<td>1.8 0.18</td>
<td>90x90x39</td>
<td>90°</td>
<td>180x134</td>
<td>180x134</td>
<td>True sagittal</td>
</tr>
</tbody>
</table>

TR: Repetition time; TE: Echo Time; FOV: Field of view; PDW: proton-density weighted; 3-D: 3-dimensional; HR: high resolution; TSE: turbo spin echo; SENSE: sensitivity encoding; SPAIR: spectrally adiabatic inversion recovery; clear: constant level appearance
This protocol had been previously standardized and regarded as suitable to be performed in clinical cases, since diagnostic image quality was considered good and acquisition time is only 22 minutes (total examination time is about 40 minutes including positioning, reference scan, survey, and sequence planning).

After the MR scan, digital radiographs of the affected stifle in medial-lateral and caudal-cranial orthogonal planes were made. The patients were then moved to the operation room, in order to validate the MR and radiographic findings; in all cases, and as part of the planned surgical procedure, a lateral parapatellar arthrotomy was made and the joint was explored. The surgeons exposed the menisci, displacing the tibia cranially by using a Hohmann elevator, and palpated them using an exploration probe. The lateral and medial articular surfaces of the femur and the articular surface of the patella were exposed using a Langenbeck retractor. Joints were treated intra-operatively, according to each particular patient’s pathologic changes, and a previously described extracapsular technique [12] was used to stabilize them. Postoperative recovery was uneventful.

With regard to the MR, the signal intensity of the cranial and caudal cruciate ligament (CdCL) was evaluated. Changes in signal intensity, as well as evidence of meniscal rupture, defined as the presence of linear increased intrameniscal signal intensity penetrating a meniscal surface, or the presence of complex signal changes or meniscal distortion (representing longitudinal or bucket handle tears) [10] were recorded for each meniscus. Degree of cartilage damage and degree of osteoarthritis were recorded according to a scoring system (Table 2; Figures 1 and 2) [6, 13]. The only parameter evaluated on the radiographs was the degree of osteoarthritis, using the same scoring system as for the MR examination.

In order to minimize intra-examiner variation, and to avoid under or over interpretation of the findings, a set of reference images (for each score and each evaluated parameter) was provided; the use of reference images has been previously reported to increase the accuracy of such studies [6]. These images were obtained, in the case of healthy stifle joint stifles, from patients which were under MR examination as part of another study (not yet published); in the case of the diseased joints, images were obtained from previous patients admitted to the
hospital, as well as some of the patients enrolled in this study. The evaluator was a postgraduate veterinarian with clinical training and experience in MR interpretation, particularly of joint disease (VGZ), who initially became familiar with the reference images, and then proceeded to evaluate those of the patients; he was blind to the animal examined and to the surgical findings of each animal. Additionally, MR images and radiographs of 3 healthy patients were included. All images were analyzed using a high-resolution diagnostic screen.

| Table 2. Scoring system to grade osteoarthritis and cartilage damage used in this study |
|---------------------------------|-----------------|-----------------|-----------------|
| Parameter                       | Scoring system                          | Radiography | MR | Surgery |
| Cartilage damage*              | Smooth and regular cartilage            | Ø            | 0  | 0       |
|                                | Mild irregular surface                   | Ø            | 1  | 1       |
|                                | Partial thickness erosion                | Ø            | 2  | 2       |
|                                | Ulceration and exposition of subchondral bone | Ø            | 3  | 3       |
| Osteoarthritis**               | Osteophytes absent                      | 0            | 0  | 0       |
|                                | Osteophytes present on patella and proximal aspect of femoral trochlear groove | 1            | 1  | 1       |
|                                | Osteophytes present on patella, femoral trochlear groove, medial and lateral femoral condyles and tibial plateau | 2            | 2  | 2       |
|                                | Severe osteophytes on patella, femoral trochlear groove, medial and lateral femoral condyles and tibial plateau | 3            | 3  | 3       |

MR = Magnetic resonance
* Modified from: Olive et al. 2010; ** Modified from: Moreau et al. 2003
Figure 1. Examples of PDW images (sagittal plane) in which the degree of cartilage damage was correctly graded, according to the scoring system provided (see Table 2). The arrows indicate representative areas of cartilage lesion. A (Score 0): Smooth and regular cartilage; B (Score 1): Mild irregular surface; C (Score 2): Partial thickness erosion; D (Score 3): Ulceration and exposition of subchondral bone.
Figure 2. Examples of PDW images (dorsal plane) illustrating the osteoarthritis scoring system. The images belong to patients correctly graded according to the scoring system described in Table 2. A (Score 0): Osteophytes absent. B (Score 1): Osteophytes present on patella (not shown) and proximal aspect of femoral trochlear groove (arrow). C (Score 2): Osteophytes present on patella (white arrow), femoral trochlear groove (yellow arrow), medial and lateral femoral condyles (orange arrows) and tibial plateau (green arrow). D (Score 3): Severe osteophytes on patella (not shown), femoral trochlear groove (yellow arrow), medial and lateral femoral condyles (orange arrows) and tibial plateau (green arrow).
5.3.1 Statistical analyses

For the presence or absence of lateral and medial meniscal rupture, the sensitivity and specificity of the diagnosis were calculated (including 95% confidence intervals). A Fisher's Exact Test was performed to observe the association between rows and columns and was considered statistically significant if \( p < 0.05 \). Inter-examiner agreements in the MR diagnosis of meniscal rupture were evaluated, using a Cohen’s kappa coefficient (\( \kappa \)), taking the simple \( \kappa \) value, as this is the only possible to calculate when there are only 2 scoring possibilities.

A Cohen’s kappa coefficient (\( \kappa \)) was used to assess the agreements between the parameters cartilage damage and osteoarthritis vs. the surgical findings. Since these parameters had more than 2 scoring options, the weighted \( \kappa \) value was taken, as it takes into account the extent to which the evaluations disagree [14]. Intra-examiner \( \kappa \) for the diagnosis of osteoarthritis (MR vs. radiography) was also calculated. Agreements were described as no agreement (<0.1000), weak (0.1000 – 0.4000), clear (0.4100 – 0.6000), strong (0.6100 – 0.8000) and almost perfect (0.8100 – 1.0000) [15].

Sensitivities and specificities (including their confidence intervals) as well as the Fisher's Exact Test were calculated using GraphPad Prism® Version 4. GraphPad Software, Inc. La Jolla, California, USA. \( \kappa \) calculations were performed using SAS for Windows® SAS 9.2 TS Level 1M0. – SAS Institute Inc, Cary, NC, USA.

5.4 Results

Twenty-one dogs were included in the study. All dogs were lame before surgery and the joints required surgery. Breeds included eight mixed-breed dogs, four Labrador Retrievers, two Beagles, and one German Shepherd, Great Dane, Boxer, Griffon, Bernese Mountain Dog, Rottweiler and Small Munsterlander. There were eleven females and ten males, with a mean age of 5.71 years (range 2–11 years) and mean weight of 31.6 kg (range 7-56 kg). Twelve left stifles and 9 right stifles were affected.

The rupture of the CrCL was confirmed during surgery; eighteen complete ruptures and 3 partial ruptures were found. All CdCLs appeared normal, with the exception of one which was considered abnormally thin.

All normal joints were identified as such, both on the MR and on the radiographic examination. One stifle was classified as normal, based on the radiographic images, which in
fact belonged to one patient with a short-lasting CCLR; the same patient showed no abnormalities (apart from the CCLR) on the MR examination.

5.4.1 Cranial cruciate ligament damage
As previously mentioned, the CCLR was confirmed during surgery in all 21 cases, finding 18 complete ruptures and 3 partial ruptures. However, the evaluator diagnosed a partial rupture on the MR images in two cases, even though the ligaments showed a complete rupture in the surgical exploration; in another three cases the evaluator diagnosed a complete rupture of the CrCL on the MR exam, but a partial rupture was observed at surgery. In all other cases (16) the ligament exhibited a total rupture, and it was diagnosed as such on the MR images.

5.4.2 Caudal cruciate ligament damage
All CdCLs were correctly identified as non-ruptured on the MR images, with the exception of one which was diagnosed as partially ruptured (Figure 3a); during surgery, this particular patient presented a macroscopically thinned (degenerated) CdCL. In spite of the fact that none of these ligaments were ruptured, another 13 patients (61.9%) showed areas of hyperintensity (Figure 3b), which were interpreted as subclinical changes, not detected at the time of surgery. The remaining CdCLs showed no changes.

5.4.3 Meniscal damage
The results of the diagnosis of meniscal lesions are presented in Table 3 and some examples are illustrated in Figure 4. It might be important to clarify that the MR diagnosis of areas of hyperintensity (H) indicates meniscal changes, but not rupture. As seen in Table 3, medial meniscal rupture was found at surgery in 18 patients (86.71%). Only one of these patients presented an additional rupture of the lateral meniscus. The remaining three patients had no meniscal pathology at surgery. The sensitivity and specificity of the MR diagnosis of meniscal rupture, for each meniscus, as well as the results of the Fisher's exact test, were calculated and are summarized in Table 4.

5.4.4 Cartilage damage
Calculated $\kappa$ values for the cartilage damage (including their agreement interpretation) are presented in Table 5.
**Table 3.** Results of the meniscal findings on the magnetic resonance (MR) examination

<table>
<thead>
<tr>
<th>Patient</th>
<th>Lateral meniscus</th>
<th>Medial meniscus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MR findings*</td>
<td>Surgical findings</td>
</tr>
<tr>
<td></td>
<td>Rupture</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>H</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>H</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>H</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td>R</td>
<td>Yes</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>13</td>
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</tr>
<tr>
<td>14</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>16</td>
<td>H</td>
<td>No</td>
</tr>
<tr>
<td>17</td>
<td>H</td>
<td>No</td>
</tr>
<tr>
<td>18</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>19</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>21</td>
<td>H</td>
<td>No</td>
</tr>
</tbody>
</table>

* Adapted from Martig et al. 2006; H = Hyperintensity (area[s] of intrameniscal increase of signal intensity without reaching any surface); R = Rupture (linear increased intrameniscal signal intensity penetrating a meniscal surface, complex signal changes or meniscal distortion); 0 = Homogeneous low signal intensity

### 5.4.5 Osteoarthritis

Calculated κ values for the osteoarthritis (including their agreement interpretation) are also presented in Table 5. An intra-observer comparison between the MR and radiographic interpretation is included.

### 5.5 Discussion

Most affected breeds in the present study were mixed-breed dogs and Labrador Retrievers, these findings being similar to previous studies [16]. All patients had been correctly diagnosed
as having CCLR before surgery and the results were as expected. The macroscopically thinned CdCL was found in a joint showing severe changes, including score 3 osteoarthritis, score 3 cartilage damage and generalized capsule thickening at surgery. Thus, the abnormal ligament was part of a whole organ (joint) disease. Even though it has been previously reported that healthy joints are easily recognized on MR images [3], and this was the case in our study, they were included in an attempt to add some accuracy to the study, since the evaluator was aware that he was evaluating images from diseased joints.

![Figure 3](image1.png)

**Figure 3.** Examples of PDW images (sagittal plane) of caudal cruciate ligament abnormalities. A: Abnormal appearance (generalized hyperintensity) of the caudal cruciate ligament (arrow) seen in one patient (see text). B: Areas of hyperintensity (arrow) found in several patients. In both cases the cranial cruciate ligament cannot be observed.

We also included radiographic images from healthy stifles and they were also easily identified as such. Whether these images from healthy joints indeed added some accuracy to the study seems, in retrospective, questionable. The joint diagnosed as normal on the radiographic examination, which belonged to a patient with CCLR, showed no pathologic changes during surgery (apart from the ligament rupture), this being explained by the fact that this animal had been lame only for 2 weeks before surgery.
Figure 4. Examples of PDW images (sagittal plane) of the meniscal findings. A: Normal medial menisci. B: Hyperintensity in the cranial horn of the lateral meniscus (arrow). C: Rupture of the caudal horn of the lateral meniscus (note the presence of increased intrameniscal signal intensity penetrating the articular meniscal surface [arrow]). D: Rupture of both the caudal and cranial horn of the medial meniscus (note the presence of complex signal changes [caudal horn] and meniscal distortion [cranial horn]).
### Table 4. Results of the magnetic resonance (MR) evaluation of meniscal rupture

<table>
<thead>
<tr>
<th></th>
<th>Surgery (rupture)</th>
<th>Surgery (no rupture)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lateral meniscus</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MR (rupture)</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>MR (no rupture)</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>Sensitivity (95% CI):</td>
<td>1.0000 (0.0250 - 1.0000)</td>
<td></td>
</tr>
<tr>
<td>Specificity (95% CI):</td>
<td>1.0000 (0.8317 - 1.0000)</td>
<td></td>
</tr>
<tr>
<td>F:</td>
<td>0.0476</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Surgery (rupture)</th>
<th>Surgery (no rupture)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Medial meniscus</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MR (rupture)</td>
<td>17</td>
<td>0</td>
</tr>
<tr>
<td>MR (no rupture)</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Sensitivity (95% CI):</td>
<td>0.9444 (0.7270 - 0.9986)</td>
<td></td>
</tr>
<tr>
<td>Specificity (95% CI):</td>
<td>1.0000 (0.2924 - 1.0000)</td>
<td></td>
</tr>
<tr>
<td>F:</td>
<td>0.0030</td>
<td></td>
</tr>
</tbody>
</table>

CI = Confidence interval; F = Fisher’s exact test p value (statistically significant if p ≤ 0.05)

### Table 5. Results of the agreements (κ) for osteoarthritis and cartilage damage scoring

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Weighted κ (95% CI)</th>
<th>Agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cartilage damage (MR vs. Surgery)</td>
<td>0.4118 (0.173 - 0.6506)</td>
<td>Clear</td>
</tr>
<tr>
<td>Osteoarthritis (MR vs. Surgery)</td>
<td>0.5333 (0.3081 - 0.7586)</td>
<td>Clear</td>
</tr>
<tr>
<td>Osteoarthritis (Radiography vs. Surgery)</td>
<td>0.5600 (0.3726 - 0.7474)</td>
<td>Clear</td>
</tr>
<tr>
<td>Osteoarthritis (Radiography vs. MR)</td>
<td>0.7896 (0.617 - 0.9622)</td>
<td>Strong</td>
</tr>
</tbody>
</table>

MR = Magnetic resonance; κ = Cohen’s Kappa coefficient; CI = Confidence interval

Diagnosing a total CCLR on MR is relatively straightforward, since the loss of fiber continuity is readily seen on the images (Figure 3); in contrast, a partial CCLR is more difficult to diagnose, as the only change observed is an increased signal intensity in the normally hypointense ligament [17]. However, the misdiagnosis of total or partial ruptures is not clinically significant since in both cases the joint shows pathologic changes [18].
The presence of areas of hyperintensity in the CdCL, very likely representing subclinical changes is an interesting finding. Previous reports of naturally-occurring CdCL damage are scarce, and none of them deal with MR imaging [19, 20]; however, one previous experimental study has described significant extracellular matrix disorganization (degenerative changes and change in the collagen fibril diameter pattern) in the CdCL of CrCL-deficient dogs, 2 years after being transected [21]. It is possible that, in initial phases of the degeneration process, an inflammatory phase takes place, leading to the hyperintensity areas seen in the present study; this has been described for the CrCL [17], and it is logical to assume that similar changes can occur in the CdCL. These lesions are not a surprising finding as it has been shown that the consequences of the experimental transection of the CrCL include a strong torsion and tensile stress on the caudal ligamentous structures of the stifle [22]. There is also a clinical study performed in large dogs suffering from CCLR, in which the CdCL was directly visualized (by arthroscopy or arthrotomy) at the time of surgical stabilization [23]. In that study 88% of the patients showed some degree of damage in the CdCL. The clinical significance of these findings is yet to be determined. However, we suggest that one reason for persistent lameness, as occasionally seen after surgical stabilization, might be in some cases caused by these changes in the CdCL. The misdiagnosis of one partial CdCL rupture on MR was the result of severe degenerative changes in this ligament; this particular patient showed severe joint lesions during surgery, including ruptures of both menisci, and had been lame for approximately 6 months. As previously mentioned, the CdCL lesion was considered to be part of a severe inflammatory process comprising the whole joint.

Meniscal damage has been reported to be present in as many as 80% of the dogs suffering from CCLR [24], the medial meniscus being the most commonly affected [16]. In our study, the incidence of ruptured medial menisci was even higher (86.71%). Although meniscal lesions are more common in patients suffering from chronic CCLR [18], in the present study there were meniscal ruptures not only in patients with chronic lameness, but also in patients which were lame for only 2 weeks. Thus, the reason for this high incidence of meniscal damage is unclear.

The presence of a high number of subclinical meniscal lesions (areas of hyperintensity) is remarkable. These lesions were not detected at surgery, as they were either the result of
subclinical, degenerative changes or were located in non-visible areas of the meniscus; both cases have been previously reported [5, 25]. These findings might be of prognostic value, since these menisci may have an increased risk of rupture after surgery. This likelihood could have been evaluated performing a follow-up study of our patients, but this was beyond the scope of this paper.

The diagnostic accuracy of the MR examination for detecting meniscal rupture was very satisfactory. Taking into consideration the few cases of lateral meniscal rupture, the sensitivity is not very accurate (100%, but with a confidence interval of 0.02500 – 1.0000), but the specificity is very high (100%, with a confidence interval of 0.8317 – 1.0000) (Table 4). In the medial meniscus a different situation was seen: MR had a higher and more reliable specificity than sensitivity, due to the high number of ruptured medial menisci (Table 4). Looking at the confidence intervals of the specificity for the medial meniscus (0.2949 – 1.0000), MR had a lower specificity in the medial meniscus than in the lateral meniscus. A previous human study reviewing 59 papers, which evaluated 7367 MR scans and 5416 arthroscopies, also found a lower specificity in the medial meniscus, in comparison to the lateral one [4]. Looking at the veterinary literature, a previous study did not find LF MR imaging useful for diagnosing meniscal tears in dogs [2]. However, another study using a HF MR imaging (1.5 T) found a global sensitivity of 100% and a specificity of 94% for the diagnosis of meniscal tears, using PD TSE sequences [3]. These sequences are similar to those used in our study, indicating that the results are reliable, especially considering the stronger magnetic field of our scan. If we keep in mind that any diagnostic method used to diagnose a meniscal rupture should be highly sensitive, with a reasonably high specificity [2], the results of the present study are encouraging. Additionally, the F values (indicating row/column association) for both menisci are statistically significant (Table 4). In spite of this, some patients can still be misdiagnosed as having a tear, leading to an unnecessary arthrotomy. Hence, it seems clear that accurate MR interpretation of meniscal damage is more than challenging and that drawing the line between subclinical and clinically relevant changes is a difficult task.
Cartilage damage scoring less than satisfactory: agreement was clear but, the confidence interval was very wide. These results agree with previous human studies, which have shown to date that MR cannot replace direct visualization for diagnosing cartilage damage in the stifle [26, 27]. However, a recent study performed to evaluate the metacarpophalangeal articular cartilage in horses has shown that it is possible to satisfactorily evaluate cartilage thickness and structure using a fat-suppressed spoiled gradient-recalled imaging technique [28]. Thus, it is possible that a small increase in acquisition times and/or the use of other sequences can improve the diagnostic accuracy of cartilage damage grading in dogs.

With regard to osteoarthritis scoring, a clear agreement was also found between the surgical and the MR findings, as well as between the surgical and radiographic findings; besides, κ values and confidence intervals were similar. Additionally, the radiographic and MR scorings showed a strong agreement with each other. These data indicate that the evaluator scored osteoarthritis similarly with both methods. Thus, our study shows that 3 T MR imaging is not more accurate than radiography for the diagnosis of stifle osteoarthritis, suggesting that radiography is still a valuable imaging modality. These results disagree with previous experimental studies, in which MR imaging was found to be more sensitive than radiography for detecting osteoarthritic changes, such as early osteophyte formation [1, 29].

5.6 Limitations

Our study provided new information; however, there were limitations, such as small sample size and lack of intra-observer variability assessment. Even though images of normal joints were included, they were easily identified; thus, the evaluator was always aware that he was assessing a diseased joint. Another limitation was the lack of a group assessment to find a consensus in the diagnosis of the different parameters evaluated, as regularly performed for clinical cases in our institution. Finally, the absence of a board-certified radiologist for interpretation of the images is a limitation of the study.

5.7 Conclusions

In this study, the usefulness of 3 T MR imaging for assessing different joint pathologies associated to a CCLR was evaluated. Parameters such as cruciate ligament rupture, presence of meniscal lesions and degree of osteoarthritis could be properly assessed by the experienced evaluator. It should be kept in mind that in the case of meniscal evaluation, some margin for
misdiagnosis is present, and this might possibly lead to unnecessary surgical explorations. It was remarkable that image quality allowed a relatively accurate diagnosis of the most clinically relevant parameters, even in the smallest patient (7 kg), again, provided the evaluation is performed by an experienced person. The results clearly demonstrated the usefulness of both imaging techniques for diagnosing internal joint derangements and, at the same time, the need for adequate training and experience to evaluate stifle pathologic changes using MR images. It would have been possible to increase acquisition times, in order to improve MR image quality, and the accuracy of the diagnosis; however, one important goal of this study was to keep examination times short, to make it clinically applicable. Future studies could focus on standardizing sequences which could improve image quality of all stifle structures, while keeping the examination times to a minimum.

5.8 Competing interests
The authors declare that they have no competing interests.

5.9 Authors’ contributions
VGZ participated in study design, developed the scoring system, performed data collection and analysis, read the images and wrote the manuscript.
PD and DCW performed the MRs.
IN had the original conception of the project, participated in study design and approved the final version of the research project and the final manuscript.
PW designed the study, read the images and coordinated, approved and supervised all aspects of the study.
All authors have critically revised the manuscript and read and approved the final manuscript.

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this study. As well, we wish to thank Dr. Beate Länger for performing some of the MRs, Dr. Martin Beyerbach for his statistical assistance and the patients’ owners for their cooperation.

5.11 Endnotes

a Vetranquil® 1%: Albrecht GmbH, Aulendorf, Germany; b L-Polamivet®: Intervet Deutschland GmbH, Unterschleißheim, Germany; c Narcofol® 10 mg/ml: CP-Pharma Handelsgesellschaft GmbH, Burgdorf, Germany; d Isofluran CP®: CP-Pharma Handelsgesellschaft GmbH, Burgdorf, Germany; e Rimadyl® Injektionslösung: Pfizer GmbH, Berlin, Germany; f Philips Achieva 3.0T X-series MRI. Philips Healthcare, Hamburg, Germany; g Achieva 3.0T Musculoskeletal SENSE Flex S coil 2 elements; h Philips BuckyDiagnost and Philips Optimus 80. Philips Medical Systems DMC GmbH, Hamburg, Germany; i EIZO RadiForce™ RX211 Medical color LCD monitor. Enzo Nanao Corporation, Hakusan, Ishikawa, Japan.

5.12 References


6. General discussion

The main goal of this thesis was to use advanced diagnostic methods to study three common disorders of the locomotion in dogs. Thus, computerized gait analysis and diagnostic imaging were used to gather objective information about the outcome of hind limb amputated patients (i.e. to investigate how the dog adapted to the new locomotory status) and the outcome of patients suffering from unilateral medial coronoid process disease (MCPD), after being treated by partial coronoidectomy performed arthroscopically. Furthermore, this thesis aimed at determining the usefulness of high-field (HF) magnetic resonance MR, in the diagnosis of joint lesions associated with a CCLR in dogs, by looking at the agreement between the images obtained with a state-of-the-art 3 Tesla (T) MR scan and the actual surgical findings.

6.1 Manuscript I (Hind Limb Amputations)

6.1.1 Materials and methods

Computerized gait analysis was performed before and after the amputation of a hind limb in order to investigate how the patients adapted to the new kind of locomotion. As explained in the literature review, there is only one previously published report objectively evaluating the gait of amputated dogs (KIRPENSTEIJN et al. 2000). In that study, only kinetic gait analysis was performed, with a very limited number of animals. Therefore, objective information about the compensation of a lost hind limb and the adaptation to the new locomotory situation in amputated patients is very limited. This lack of objective information prevents the veterinarian from providing the owners with accurate information about their main concerns: that the amputation may affect the dogs emotionally, as it indeed happens in people (KIRPENSTEIJN et al. 1999; SCHULZ 2009), or that it will be disabling for the animal. Owners might be emotionally affected as well, since they are often confronted with people who refer to them as animal abusers.

In the literature review several clinical studies are mentioned, in which a high owner satisfaction after the amputation of a limb was reported (WITHROW and HIRSCH 1979; CARBERRY and HARVEY 1987; KIRPENSTEIJN et al. 1999; VON WERTHERN et al. 1999). Besides, it was stated that the fact that the owner is satisfied does not necessarily mean
that the amputation does not lead to underlying structural and/or pathologic changes in the animal, as a result of the changed weight bearing situation. Thus, an MR examination of the contralateral stifle was performed under general anesthesia before and 120 days after amputation, in order to evaluate the possible presence of post-operative changes.

Another important factor already mentioned is that, even though the best way to evaluate changes in locomotion is by performing prospective studies, the few existing studies with amputee patients are retrospective, and all of them use subjective parameters to evaluate the animals. Prospective studies with animals which need to be amputated are lacking, and the kinematics (joint movement) and possible joint changes after a hind limb amputation in dogs have never been evaluated. When this information is available, owners will receive a more accurate and objective advise when facing the decision to amputate their dogs.

To be able to compare the results of this part of the thesis with the literature, owners were requested to fill out an evaluation form modified from a previous study (HIELM-BJORKMAN et al. 2003) before and after amputation to assess their (subjective) impressions with regard to patient comfort and recovery; these results were compared to those (objective) of the gait analysis. Additionally, owners also filled out a questionnaire to assess their final impression regarding the degree of activity and the life quality of the dog, and their general impression and satisfaction with the procedure, at the end of the study (day 120). The questions of the questionnaire were adapted from several sources (WITHROW and HIRSCH 1979; CARBERRY and HARVEY 1987; KIRPENSTEIJN et al. 1999; VON WERTHERN et al. 1999).

**6.1.2 Results**

The results of the kinetic and kinematic analyses before and after amputation revealed that the adaptation process to the new locomotory situation began even before the amputation was performed. Furthermore, it could be observed that 10 days after the procedure, all significant changes had already taken place, and that the new locomotion remained stable during the time between 10 and 120 days after the procedure.
The MR examination found no changes in the remaining contralateral knee after amputation; this could mean that an overload in the remaining contralateral hind limb, leading to joint pathology, is not very likely. It was decided to investigate this point, as it is commonly believed by patient owners, and even by some Veterinarians, that the amputation might predispose the animal to orthopedic abnormalities. The results of our MR (and also our clinical examinations) proved no pathologic joint changes within the time course of 120 days after amputation, at least for the stifle joint. However, measuring cartilage thickness would have been a more accurate method to evaluate subtle joint changes (BOILEAU et al. 2008). Unfortunately, this could not be done due to software limitations.

The questionnaires revealed that owners soon realized that their fears about the negative consequences of the amputation were unfounded. Most owners were first reluctant to have their dogs amputated, but were finally satisfied with the overall result of the amputation and considered the life quality of their dogs as good. These findings are in agreement with other sources (WITHROW and HIRSCH 1979; CARBERRY and HARVEY 1987; KIRPENSTEIJN et al. 1999; VON WERTHERN et al. 1999). In the present study some owners even considered that their pet’s quality of life improved after amputating, and that this might have been related to the removal of the source of pain.

These are all very positive results, indicating that the amputation of a hind limb has no deleterious effects in dogs, at least up to 4 months after the procedure. Besides, the data presented in this part of the thesis have the advantage of looking at the patients objectively and prospectively, leaving no doubt about the fast adaptation to the new movement situation of all animals.

One important limitation of this part of the thesis is the relatively short postoperative period of time in which the animals were investigated, especially regarding the MR examination. Although four months after surgery is a short time to evaluate joint changes, a previous study describing the experimentally induced rupture of the CrCL in 5 crossbred dogs showed that it is possible to detect changes in the cartilage and subchondral bone as early as 4 weeks after the rupture (BOILEAU et al. 2008). It is of course difficult to extrapolate such findings to the
present study, but could indicate that, if there were ongoing changes in joint morphology, they would be visible 4 months after amputation.

6.1.3 Conclusions

From this part of the thesis it can be concluded that, in spite of the limitations (very heterogeneous population and a relatively small number of patients), convincing and objective evidence was found, indicating that dogs have a quick adaptation process after a hind limb amputation, at least up to four months after the procedure. The adaptative processes to the new locomotion began even before the amputation was performed. Since proper advise has to be given by the veterinarian before an amputation is carried out (WEIGEL 2003), it is strongly believed that this work provides useful information which will allow veterinarians to be able to give dog owners a more realistic explanation of what to expect after a hind limb amputation.

6.2. Manuscript II (Medial Coronoid Process Disease)

6.2.1 Materials and methods

Fourteen dogs with forelimb lameness confirmed to be caused by unilateral medial coronoid process disease (MCPD) were included in this study. Kinetic analysis of both forelimbs, along with kinematic analysis and goniometry of both elbows were carried out before and 60, 120 and 180 days after partial coronoidectomy performed by arthroscopy. Radiography and computed tomography of both elbows were also carried out before and 180 days after the arthroscopy.

Recent studies using inverse dynamics methods of gait analysis (BURTON et al. 2011) and measurements of peak vertical forces, vertical impulse and goniometry (BUBENIK et al. 2002) concluded that arthroscopy is not superior to medical treatment (BURTON et al. 2011) or to arthrotomy (BUBENIK et al. 2002) for treating MCPD. These data refute the results of previous studies which, using subjective methods, indicated that arthroscopy is the gold standard to treat MCPD (MEYER-LINDENBERG et al. 2003; EVANS et al. 2008). Therefore, the general belief of excellent recovery after the arthroscopic treatment of MCPD might be a myth, this being the main reason to carry out the study described in manuscript II.
Computerized gait analysis was considered necessary for performing this study, since Burton et al. (2009) found that, in comparison to kinetic and kinematic analysis, the subjective assessment of the gait by owners and veterinarians is not reliable to evaluate pain and degree of lameness in patients with forelimb lameness caused by MCPD. Both loads and the symmetry index (SI) were calculated. In order to be able to compare the results of the SI with the morphologic findings, a symmetry index score (SIS) was made.

In this part of the thesis other diagnostic methods were included: goniometry, radiography and computed tomography. Goniometry has been seldom used to investigate the motion characteristics of the elbow in patients suffering from MCPD. Only one previous study (BUBENIK et al. 2002) comparing the range of motion (ROM) of patients which underwent arthrotomy or arthroscopy is available. Furthermore, in that study the comparisons were made only for 29 days after surgery. In the present thesis a long-term attempt to find changes in the maximal extension and flexion angles, as well as in the ROM was made. The radiographic and computed tomographic examinations were performed under general anesthesia 1-3 days before and 180 days after the arthroscopy. Radiography was performed to detect and quantify joint changes (using an osteophyte score [OS]), both before and after the arthroscopy, and to correlate these data with the results of the kinetic and kinematic gait analysis. CT examinations were necessary to ascertain that the contralateral healthy joints remained free of disease during the study.

6.2.2 Results

The results of the kinetic analysis (PFz and SI) indicate that during the 6-month period of evaluation, even though there was improvement, most patients did not reach complete restoration of function. Although these results are somewhat surprising, a previous study using total support moment ratios to evaluate the symmetry of the forelimbs found that patients may need more than 12 months to fully recover after a partial coronoidectomy performed by arthroscopy (BURTON et al. 2009). The kinematic analysis provided similar results: there were no significant differences in the maximal extension and flexion angles, as well as in the ROM, both between sessions (before and after surgery) as well as within sessions (when comparing healthy vs. affected side). Thus, the kinetic parameters do not correlate with the kinematic parameters. However, a decrease in the ROM and an increase in
the maximal flexion angle (both indicating less joint mobility) in the affected elbow were observed, and seemed to be directly related to an increase in the OS. With respect to the goniometric measurements of joint mobility, the fact that the maximal extension and flexion angles and the ROM measured by this technique did not differ between sessions, very similar to the kinematic results, indicate that there were in fact subtle changes in the ability of the affected joint to move, as time elapsed. However, when comparing healthy vs. affected side within sessions, goniometry seemed to reflect more accurately the changes happening in the joint: an increased maximal flexion angle and a decreased ROM indicate that the affected elbows had in fact passive mobility impairment. In spite of this, the ability of the joint to move actively during locomotion was not affected, which may explain why, even though OS worsened, the animals were able to recover from the lameness.

As previously mentioned, all affected elbow joints showed an increase in the OS. This is remarkable, specially taking into consideration the fact that eight patients showed no signs of osteoarthritis before the arthroscopy. Although this is an expected result, based on previous studies (HUIBREGTSE et al. 1994; INNES et al. 2004; FITZPATRICK et al. 2009a) it is disappointing to find that the coronoidectomy does not prevent, and apparently does not slow down, osteoarthritis development.

When looking at the OS and the SIS, it is clear that there was no correlation between the morphologic and functional findings. This is in agreement with other previous studies (READ et al. 1996; THEYSE et al. 2000; GORDON et al. 2003; RAYWARD et al. 2004; FITZPATRICK et al. 2009b), and possibly indicates that the lameness was a direct result of the inflammatory process caused by the pathologic coronoid process within the joint, and not the result of the osteoarthritis as such.

Finally, the CT evaluation of both elbow joints before and after the arthroscopy was made to confirm that the MCPD was present only in one elbow, and to confirm that the contralateral elbow remained unchanged during the whole observation period of 6 months after surgery. In order to be able to make a correct interpretation of the kinetic, kinematic and goniometric data of the affected joint, it was essential that the contralateral elbow remained unaltered.
throughout the study. The diagnosis of MCPD was made using CT, as it is a reliable imaging method, even in cases where there are no evident radiographic changes indicating the presence of MCPD (ROVESTI et al. 2002; PUNKE et al. 2009). On the other hand, the diagnosis of MCPD using only radiographs is difficult (REICHLE et al. 2000; FITZPATRICK et al. 2009b).

6.2.3 Conclusions

It can be concluded that the arthroscopic intervention of medial coronoid process disease led to functional improvement of the kinetic parameters only, without full restoration of function. The kinematic parameters showed no improvement. Morphologically (degree of osteoarthritis) and mechanically (goniometry), there was even a worsening of the affected joint. Thus, this work indicates that the arthroscopic treatment of MCPD is of limited benefit. Even though there are some previous studies reporting similar results (HUIBREGTSE et al. 1994; BURTON et al. 2011), this is the first study that looks simultaneously at several objective functional and morphologic parameters to quantify the outcome of actual patients after the arthroscopic treatment of unilateral MCPD. More studies comparing different treatment modalities, which look at objective, measurable parameters, performed in a larger patient population, are needed to further evaluate these findings.

6.3 Manuscript III (Cranial Cruciate Ligament Rupture)

6.3.1 Materials and methods

The diagnostic accuracy of a short-duration magnetic resonance (MR) protocol, using a 3 Tesla (T) MR magnet for evaluating cranial (CrCL) and caudal (CdCL) cruciate ligament, meniscal and cartilage damage, as well as degree of osteoarthritis was assessed in 21 dogs affected by naturally-occurring cranial cruciate ligament rupture (CCLR). For this purpose, a state-of-the-art 3 T MR scan was used to obtain images from the affected stifle, using a protocol that had been previously standardized and regarded as suitable to be performed in clinical cases, since diagnostic image quality was considered good and acquisition time is only 22 minutes (total examination time is about 40 minutes including positioning, reference scan, survey, and sequence planning). There are other studies in the literature using similar protocols (KONAR et al. 2005a, b; BLOND et al. 2008). Digital radiographs of the affected
General discussion

stifle in medial-lateral and caudal-cranial orthogonal planes were also made. As part of the planned surgical procedure, a lateral parapatellar arthrotomy was performed, the joint was explored, and the morphological joint status was recorded for the later comparison with the MR and radiographic analyses. Joints were treated intra-operatively according to each particular patient's pathologic changes and stabilized by means of a previously described extracapsular technique (BÖDDEKER et al. 2012).

With regard to the MR, the signal intensity of the CrCL and CdCL was evaluated. Changes in signal intensity, as well as evidence of meniscal rupture, defined as the presence of linear increased intrameniscal signal intensity penetrating a meniscal surface, or the presence of complex signal changes or meniscal distortion (representing longitudinal or bucket handle tears) (MARTIG et al. 2006) were recorded for each meniscus. Degree of cartilage damage and degree of osteoarthritis were recorded according to a scoring system (MOREAU et al. 2003; OLIVE et al. 2010). The only parameter evaluated on the radiographs was the degree of osteoarthritis, using the same scoring system as for the MR examination.

In order to have reference images to compare, for each evaluated parameter a guide of the scoring system was made, taking normal animals, previous patients, and some of the patients of this part of the thesis. The use of reference images has been previously reported to increase the accuracy of this kind of studies (OLIVE et al. 2010). Additionally, MR images and radiographs of three healthy patients were included.

6.3.2 Results

All normal joints were identified as such, both on the MR and on the radiographic examination. The CCLR was confirmed during surgery in all cases (21 dogs), finding 18 complete ruptures and three partial ruptures. However, a partial rupture on the MR images was diagnosed in two cases, even though the ligaments showed a complete rupture in the surgical exploration; in another three cases a complete rupture of the CrCL was diagnosed on the MR exam, even though a partial rupture was observed at surgery. In all other cases (16) the ligament exhibited a total rupture, and it was diagnosed as such on the MR images. Diagnosing a total CCLR on MR is relatively straightforward, since the loss of fiber continuity is readily seen on the images; in contrast, a partial CCLR is more difficult to
diagnose, as the only change observed is an increased signal intensity in the normally hypointense ligament (GAVIN and HOLMES 2009). However, the misdiagnosis of total or partial ruptures is not clinically significant since in both cases the joint shows pathologic changes (HAYASHI et al. 2010).

In spite of the fact that none of the CdCLs were ruptured, 13 patients (61.9%) showed areas of hyperintensity, which were interpreted as subclinical changes, not detected at the time of surgery. These areas of hyperintensity, very likely representing subclinical changes, are interesting: previous reports of naturally occurring CdCL damage are scarce, and none of them deal with MR imaging (WONG 1994; LORINSON et al. 2000); however, one previous experimental study has described significant extracellular matrix disorganization (degenerative changes and change in the collagen fibril diameter pattern) in the CdCL of CrCL-deficient dogs, 2 years after being transected (ZACHOS et al. 2002). It is possible that, in initial phases of the ligament degeneration, an inflammatory process takes place, which corresponds to the hyperintensity areas as seen in the present study. An identical MR morphology has been described in the CrCL degenerated CrCL (GAVIN and HOLMES 2009), and it is logical to assume that similar changes can occur in the CdCL. Additionally, there is a clinical study performed in large dogs suffering from CCLR, in which the CdCL was directly visualized (by arthroscopy or arthrotomy) at the time of surgical stabilization (SUMNER et al. 2010). In that study 88% of the patients showed some degree of damage in the CdCL. The clinical significance of these findings has, however, yet to be determined.

Meniscal damage has been reported to be present in as many as 80% of the dogs suffering from CCLR (GAMBARDELLA et al. 1981), and the most commonly damaged meniscus is the medial one (LAMPMAN et al. 2003). In this work, the incidence of ruptured medial menisci was even higher (86.71%). Although meniscal lesions are more common in patients suffering from chronic CCLR (HAYASHI et al. 2010), in the present study there were meniscal ruptures not only in patients with chronic lameness, but also in patients which had been lame for only 2 weeks. Thus, the reason for this high incidence of meniscal damage is unclear.
The diagnostic accuracy of the MR examination for detecting meniscal rupture was very satisfactory. However, there were only a few cases of lateral meniscal rupture, making the sensitivity not very accurate, but the specificity very high. In the medial meniscus a different, yet satisfactory situation was seen: MR had a higher and more reliable specificity than sensitivity, due to the high number of ruptured medial menisci. Looking at the confidence intervals of the specificity for the medial meniscus, MR had a lower specificity in the medial meniscus than in the lateral meniscus. This is in agreement with a previous human study reviewing 59 papers, which evaluated 7367 MR scans and 5416 arthroscopies (CRAWFORD et al. 2007). Looking at the veterinary literature, a previous study did not find low-field MR imaging useful for diagnosing meniscal tears in dogs (BÖTTCHER et al. 2010). However, another study using high-field MR imaging (1.5 T) found a global sensitivity of 100% and a specificity of 94% for the diagnosis of meniscal tears (BLOND et al. 2008).

Even though better agreements were expected, osteoarthritis and cartilage damage could be properly assessed using both MR and radiography. However, the findings of this study indicate that 3 T MR imaging is not more accurate than radiography for the diagnosis of knee osteoarthritis, suggesting that radiography is still a valuable imaging modality. These results disagree with previous experimental studies, in which MR imaging was found to be more sensitive than radiography for detecting osteoarthritic changes, such as early osteophyte formation (NOLTE-ERNSTING et al. 1996; D’ANJOU et al. 2008).

6.3.3 Conclusions

Cruciate ligament rupture, presence of meniscal lesions and degree of osteoarthritis and cartilage damage could be properly assessed using 3 T MR images. It should be kept in mind that in the case of meniscal evaluation, some margin for misdiagnosis is present, and this might possibly lead to unnecessary surgical explorations. It was remarkable that image quality allowed a relatively accurate diagnosis of the most clinically relevant parameters, even in the smallest patient. The results clearly demonstrated the usefulness of both imaging techniques (3 T MR and radiography) for diagnosing internal joint derangements. In order to improve MR image quality and the accuracy of the diagnosis, it would have been possible to use longer acquisition times. However, one important goal of this work was to keep examination times short, to make it clinically applicable. Future studies could focus on standardizing
sequences which could improve image quality of all knee structures, while keeping the examination times to a minimum.

6.4 Concluding remarks

The results of this thesis show that the combination of diagnostic tests for evaluating morphological and/or functional parameters leads to an improvement of the diagnostic process and/or understanding of the outcome in patients suffering from orthopedic disease.
7. Summary

Vladimir Galindo-Zamora

Selected clinical studies on canine joint function and morphology using computerized gait analysis and diagnostic imaging

To date, combined functional and morphological investigation methods are not routinely used for diagnosis and follow up of orthopedic diseases. Thus, the main goal of this thesis was to use a combination of advanced diagnostic methods to study three common disorders of the locomotion in dogs. Computerized gait analysis and diagnostic imaging were used to gather objective information about the outcome of patients which had undergone a hind limb amputation (i.e. to investigate how the dog adapted to the new locomotory status), and the outcome of patients suffering from unilateral medial coronoid process disease after being treated by partial coronoidectomy, performed arthroscopy. Furthermore, this thesis aimed at determining the usefulness of high-field magnetic resonance in the diagnosis of joint lesions associated with a cranial cruciate ligament rupture in dogs by looking at the agreement between images obtained with a state-of-the-art 3 T MR Scan and the actual surgical findings.

For the first part of the thesis (manuscript I) 12 patients of different breeds, sex and ages, in which a hind limb amputation was scheduled, were included. Kinetic (forces) and kinematic (movement) gait analysis was performed one to three days before the amputation, as well as 10, 30, 90 and 120 days after surgery. Kinetic data showed that 10 days after amputation there was redistribution of the load to all remaining limbs, this weight bearing shift being more important towards the forelimbs. The recorded kinetic data showed no remarkable changes during the remaining examination time points, indicating that 10 days after amputation patients had already established their new locomotory pattern. Kinematic data showed significant differences between sessions in the mean angle progression curves of almost all joint angles; however, the ranges of motion of the analyzed joints were very similar before and 10 days after amputation and remained constant in the subsequent sessions. No changes in the signal intensity of the cranial and caudal cruciate ligaments or the lateral and medial menisci were found on the MR evaluation of the contralateral stifle. Besides, no evidence of
cartilage damage or osteoarthritis was seen. Finally, owners evaluated the results of the amputation very positively, both during and at the end of the study. It was concluded that dogs have a quick adaptation to the new locomotory situation after a hind limb amputation, and that the adaptation process begins even before the amputation is performed. This happens without evidence of morphologic changes in the stifle joint, and with a very positive evaluation from the owner.

In the second study (manuscript II), 14 dogs with forelimb lameness confirmed to be caused by unilateral medial coronoid process disease were included. Kinetic analysis of both forelimbs, along with kinematic analysis and goniometry were made before and 60, 120 and 180 days after partial coronoidectomy performed by arthroscopy. Additionally, radiography and computed tomography of both elbows were carried out before and 180 days after the procedure. A non-significant ($p=0.1093$) increase in the loads applied by the affected limb was seen. When comparing healthy vs. affected side, there were highly significant differences in the mean loading forces in all sessions. The symmetry index improved, with significant differences between sessions ($p=0.0190$). However, kinematic parameters showed no significant differences, neither between sessions nor when comparing healthy vs. affected side within sessions. Goniometry showed no significant differences between sessions, but some significant differences were found when comparing healthy vs. affected side within sessions. There was no correlation between osteophytosis and degree of lameness, neither before ($r_s=-0.07683; p=0.7940$) nor after arthroscopy ($r_s=0.2700; p=0.3505$). It was concluded that only the kinetic parameters improved after arthroscopy, without full restoration of function. The kinematic parameters showed no improvement. Furthermore, osteoarthritis and goniometric measurements in the affected joint worsened. Finally, the functional parameters did not correlate with the morphologic findings. This is clinically relevant, since the results of this part of the thesis showed that the arthroscopic management of medial coronoid process disease by partial coronoidectomy only led to a partial recovery of limb function.

In the third study (manuscript III), 21 client-owned dogs were included to assess the diagnostic accuracy of a short-duration magnetic resonance protocol, using a 3 Tesla magnetic resonance scan, in dogs affected by naturally occurring cranial cruciate ligament rupture with
regard to the evaluation of cranial and caudal cruciate ligament rupture, meniscal and cartilage damage, as well as the degree of osteoarthritis. Osteoarthritis scoring was also performed using digital radiographic images. One veterinarian with experience in the assessment of magnetic resonance imaging of joint disease evaluated all images, and the results were compared with the actual surgical findings observed during arthrotomy. The evaluator correctly identified all cranial cruciate ligaments as ruptured. With one exception, all caudal cruciate ligaments were correctly identified as non-ruptured. High sensitivities and specificities were obtained when diagnosing meniscal rupture. Additional lesions could be observed, both in the cranial and caudal cruciate ligaments and in the menisci; however, their clinical significance is yet to be determined. There was a clear agreement between the MR and radiographic findings with regard to the parameters cartilage damage and degree of osteoarthritis. MR imaging was not superior to radiography for the assessment of osteoarthritis. It was concluded that the presence of cruciate ligament damage, meniscal rupture and degree of osteoarthritis could be properly assessed on the magnetic resonance images. However, in the case of meniscal evaluation, some margin for misdiagnosis is still present.

The results of this thesis show that the combination of diagnostic tests for evaluating morphological and/or functional parameters leads to an improvement of the diagnosis process and/or understanding of the outcome in patients suffering from orthopedic disease.
8. Zusammenfassung

Vladimir Galindo-Zamora

Ausgewählte klinische Studien zur caninen Gelenkfunktion und -morphologie unter Verwendung computergestützter Ganganalyse und diagnostischer Bildgebung


Im ersten Teil dieser Arbeit (Manuskript I) wurden 12 Patienten verschiedener Rassen, Geschlechts und Alters, bei denen eine Hintergliedmaßenamputation geplant war, aufgenommen. Die kinetischen Daten zeigten, dass 10 Tage nach Amputation das Gewicht auf alle verbleibenden drei Gliedmaßen umverteilt war, wobei die Verschiebung der Belastung deutlich in Richtung der Vordergliedmaßen ging. Die gemessenen kinetischen Daten wiesen keine bemerkenswerten Veränderungen während den übrigen Messzeitpunkten auf, was zeigt, dass bereits 10 Tage nach Amputation die Patienten ihren neuen Fortbewegungsmodus angenommen haben. Die kinematischen Daten wiesen signifikante

In die zweite Studie (Manuskript II) wurden 14 Hunde mit Vorderbeinlahmheit auf Grund einer nachgewiesenermaßen unilateralen Koronoiderkrankung aufgenommen. Die kinetische und kinematische Analyse beider Vorderbeine sowie die Goniometrie wurden sowohl vor als auch 60, 120 und 180 Tage nach der partiellen Koronoidektomie mittels Arthroskopie durchgeführt. Vor und 180 Tage nach Arthroskopie wurden außerdem Röntgen- und computertomographische Aufnahmen beider Ellbogengelenke angefertigt. Ein nicht signifikanter Anstieg (p=0,1093) der Belastung der betroffenen Gliedmaße wurde festgestellt. Beim Vergleich der gesunden mit der erkrankten Seite traten hoch signifikante Unterschiede in den durchschnittlichen vertikalen Kräften in allen Sitzungen auf. Wie die signifikanten Unterschiede (p=0,0190) des Symmetrie-Indexes zeigten, verbesserte sich die Symmetrie zwischen den Sitzungen. Die kinematischen Parameter hingegen wiesen weder zwischen den einzelnen Sitzungen noch beim Vergleich der gesunden mit der erkrankten Seite innerhalb einer Sitzung signifikante Unterschiede auf. Die Goniometrie wies keine signifikanten Unterschiede zwischen den Sitzungen auf, allerdings konnten signifikante Unterschiede beim Vergleich der kranken mit der gesunden Seite innerhalb einer Sitzung nachgewiesen werden. Zwischen Osteophytose und dem Lahmheitsgrad bestand weder vor (r_s=-0.07683; p=0.7940) noch nach Arthroskopie (r_s=0.2700; p=0.3505) eine Korrelation. Zusammenfassend lässt sich
Zusammenfassung


Die Ergebnisse dieser Arbeit zeigen, dass die Kombination diagnostischer Tests, welche die morphologischen und/oder funktionellen Parameter bewerten, zu einer Verbesserung der Diagnostik bei Patienten mit orthopädischen Erkrankungen führt.
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