Sagittal joint instability in the cranial cruciate ligament insufficient canine stifle

Caudal slippage of the femur and not cranial tibial subluxation

Janna Rey[#], Martin S. Fischer*, Peter Böttcher[#]

[#]Klinik für Kleintiere, Universität Leipzig, Leipzig

*Institut für Spezielle Zoologie und Evolutionsbiologie mit Phyletischem Museum, Friedrich-Schiller-Universität, Jena

Korrespondierender Autor: Prof. Dr. Peter Böttcher, Klinik für Kleintiere, An den Tierkliniken 23, D-04103 Leipzig, Germany. Tel: +49 341 97 38 700. Fax: +49 341 97 38 799. E-Mail: boettcher@kleintierklinik.uni-leipzig.de

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Key words: Stifle, cranial cruciate ligament rupture, in vivo, kinematics, fluoroscopy

Summary

Objectives: This in vivo study qualitatively describes the sagittal motion pattern of the cranial cruciate ligament (CrCL) insufficient stifle in operated and unoperated joints with passive laxity on palpation. **Material and Methods:** In vivo sagittal stifle kinematics were recorded in dogs (>15 kg BW) with unilateral (n = 7) or bilateral (n = 6) complete CrCL rupture and positive cranial drawer test as well as two sound control dogs using uniplanar fluoroscopic kinematography with the dogs walking on a treadmill. Stifle stability and sagittal motion pattern of the femur and the tibia were determined by visual inspection of the fluoroscopic video sequences. **Results:** Control dogs showed no instability, identical to the contralateral stifles of those dogs with unilateral rupture. All unoperated stifles with CrCL rupture (n = 6) showed caudal slippage of the femur at the beginning of stance phase. Of the operated stifles (n = 13: 1 TightRope, 6 TTA, 5 TPLO, 1 CCWO) nine were unstable, showing the same motion pattern as the unoperated stifles. **Conclusion(s):** Sagittal joint instability in the CrCL insufficient stifle is characterized by caudal subluxation of the distal femur at tow touch. **Clinical significance:** The unexpected high number of operated stifles with persistent instability challenges the biomechanical effectiveness of some surgical treatments of CrCL rupture and warrants further studies.

Schlüsselwörter: Kniegelenk, Riss des vorderen Kreuzbandes, in vivo, Kinematik, Fluoroskopie

Zusammenfassung

Ziel: Diese in vivo Studie beschreibt qualitativ das sagittale Bewegungsmuster kreuzbandinsuffizienter Kniegelenke mit und ohne operativer Stabilisierung.
Material und Methoden: Die sagittale Kniegelenkskinematik wurde bei Hunden (> 15 kg KM) mit einseitigem (n = 7) und beidseitigem (n = 6) Riss des vorderen Kreuzbandes in vivo beurteilt, wobei die Hunde auf einem speziell für Hunde konstruierten Laufband liefen. Alle Gelenke waren zum Zeitpunkt der Ganganalyse palpatorisch instabil. Zwei gesunde Hunde dienten als Kontrolle. Die kranio-kaudale Kniegelenksstabilität, sowie das allgemeine sagittale Bewegungsmuster von Femur und Tibia wurden anhand uni-planarer fluoroskopischer Videosequenzen visuell beurteilt.
Ergebnisse: Die Kontrolltiere zeigten keine sichtbare kranio-kaudale Instabilität, ebenso nicht die gesunden Kniegelenke unilateral betroffener Tiere. Alle unoperierten Gelenk mit Riss des vorderen Kreuzbandes (n = 6) wissen ein kaudal gerichtetes Abgleiten des distalen Femurs entlang des Tibiaplateaus zu Beginn der Standphase auf. Bei den operierten Gelenken (n = 13: 1 TightRope, 6 TTA, 5 TPLO, 1 Keilosteotomie) wiesen neun eine Instabilität auf, identisch zum Bewegungsmuster der unoperierten instabilen Gelenke. **Schlussfolgerung:** Die sagittale Kniegelenksinstabilität im Zusammenhang mit einem Riss des vorderen Kreuzbandes ist durch eine kaudal gerichtete Rutschbewegung des Femurs beim Auffußen gekennzeichnet. **Klinische Relevanz:** Die unerwartet hohe Zahl operierter Kniegelenke mit bestehender Gelenksinstabilität stellt die biomechanische Effektivität einiger Operationsmethoden in Frage und bedarf weiterer Untersuchungen.

Introduction

The canine cranial cruciate ligament (CrCL) antagonises forces which result in cranial subluxation and to a certain degree internal rotation of the tibia relative to the femur (2). This broadly accepted concept of CrCL function has been defined based on anatomical studies (2) and static in vitro tests (1, 5, 12-14, 17, 19-23, 30), stimulating some muscle forces as well as body load acting on the stifle. The concept has been validated by two in vivo studies looking at stifle kinematics following artificial CrCL transection, providing the evidence that even during dynamic walking activity cranial subluxation of the tibia occurs at the beginning of stance phase (16, 28). However the presumed increase in internal rotation following CrCL rupture seen in vitro (2) could not be confirmed (28). Irrespectively of this discrepancy between in vitro and in vivo findings, the common understanding of stifle kinematics following CrCL rupture is driven by cranial subluxation of the tibia as the dominating disturbance. As consequence any surgical procedure aims at neutralizing cranial tibial thrust, and at providing rotational stability whenever possible. Our focus on tibial instability in the context of CrCL disease is further sustained by the fact, that clinical diagnosis of CrCL rupture is made by palpation of cranio-caudal instability of the tibia in relation to the femur (4), or by stress radiographs resulting in cranial tibial subluxation (7).

Because periarticular fibrosis and degenerative joint disease is a common finding at the time of diagnosis of CrCL rupture in canines, Pozzi and Kim (21) hypothesized that the cranio-caudal instability of the canine stifle following naturally occurring CrCL rupture would be slighter than the one after artificially induced CrCL rupture in research dogs with normal stifle joints. As a result, three-dimensional in vivo kinematics of the canine stifle joint in dogs with natural occurring CrCL pathology has recently be reported (3) Unexpectedly, cranio-caudal stifle instability following CrCL rupture seemed to be characterised by caudal slippage of the femur, a motion pattern completely different to what is currently reported in veterinary literature.

With the current study we aim at investigating the real in vivo sagittal motion pattern of the CrCL deficient stifle. Our working hypothesis was that with complete CrCL rupture and passive laxity on palpation, the femur would consistently slip caudal at the beginning of stance phase while the stifle is maximally extended, disproving the established concept of tibial instability. Furthermore, femoral instability would also be the key feature in joints with persistent cranio-caudal instability and failed surgical stabilisation.

Material and Methods

Animals

Dogs (BW ≥ 15 kg) were randomly included into the study if they were lame because of CrCL deficiency or if they had been operated before because of complete CrCL rupture. Dogs affected bilaterally were also considered candidates. For final inclusion, cranial drawer at palpation of the affected stifle(s) indicating complete CrCL rupture had to be present, whereas tibial compression test was not evaluated. Stable stifles at palpation such as cases of incomplete rupture, joints with excessive periarticular fibrosis or those with a stable extraarticular repair were excluded. This resulted in the inclusion of 19 palpatory unstable stifles (10 left, 9 right, 6 bilateral) of 13 dogs (1 neutered and 7 intact females, 5 intact males). Six stifles were unoperated, 13 had been operated at least six weeks before using different surgical methods (TightRope n = 1, tibial tuberosity advancement (TTA) n = 6, tibial plateau leveling osteotomy (TPLO) n = 5, cranial closing wedge osteotomy (CCWO) n = 1). Mean age on admission was 4.2 years (range, 1 – 9.2 years) and mean body weight was 30.1 kg (range, 16 – 49 kg). Breeds included mixed breed (3), Labrador Retriever (2), and 1 each of Rottweiler, Bullmastiff, American Canadian White Shepherd, Black Russian Terrier, Entlebucher Mountain Dog, Weimaraner, Beagle, and Akita Inu.

Two sound mixed breed dogs (1 female and 1 neutered male), eight and four years old with a body weight of 18.6 and 20.2 kg respectively served as our control group. The contralateral stifle in those dogs with unilateral CrCL pathology (n = 7) was also included in the latter.

Fluoroscopic kinematography

Using uni-planar fluoroscopic kinematography, dogs were investigated while walking on a canine treadmill (Model DC7, JOG A DOG, Ottawa Lake, Michigan, USA). Speed was set to 0.8 to 1.0 m/sec, depending on the size of the dog and the degree of lameness on the day of gait analysis. The degree of lameness on the affected limb(s) when walking on the treadmill ranged from none to mild to moderate. In all cases the radiographic beam was directed from lateral to lateral, focusing on the stifle joints and allowing good visualization of cranio-caudal stifle motion in the sagittal plane. The fluoroscopic unit (Fig. 1) consisted of a standard C-arm (BV 300, Philips Medical Systems Nederland B.V., Best, Netherland) equipped with a high-speed digital camera (CamRecord 600, Optronis, Kehl, Germany) replacing the standard video camera of the C-arm, which only allows a frame rate of 25 to 30 frames per second (27). During fluoroscopic kinematography the C-arm was operated in continuous mode at 80 to 110 kV and 2.8 to 3.1 mA depending on the body conformation of the dog. Digital recording of the fluoroscopic sequences of about four to six seconds duration was performed at a rate of 500 fr/sec and a shutter (exposure time) of 1/2000 sec. A sequence was defined to be valid if for both stifles at least three heal strikes were recorded. Optimally, the entire stance phase from heal strike to foot lift was recorded. Inevitably, in larger dogs the stifle went out of the imaging field because of the limited size of the image intensifier.

Data analysis

Video sequences were visually inspected for cranio-caudal translation between the femur and the tibia by two independent observers and finally admitted a consensus based binary score in respect to stability (stable, unstable) and motion pattern (tibial subluxation vs. femoral slippage).

Results

Both control dogs showed no visible translation between the femur and the tibia on fluoroscopy. The same was observed in the stable, contralateral stifles of those dogs with unilateral CrCL rupture. All unoperated stifles showed marked cranio-caudal instability with the femur slipping caudally, just at the beginning of stance phase (see movie 1; www.fluokin.de for further fluoroscopic images sequences). On those fluoroscopic sequences which included foot lift, spontaneous reduction of femoral subluxation occurred just at the end of stance phase. No translational movement of the tibia during stance phase was apparent. Of the operated stifles which all had positive cranial drawer test on palpation, nine proved to be unstable on fluoroscopy in the sagittal plane (1 TightRope, 4 TTA, 3 TPLO, 1 CCWO). As for the unoperated stifles, femoro-tibial motion pattern was characterised by a sudden caudally directed slippage of the femur at early stance phase and spontaneous repositioning at the end of stance phase for all but one stifle. In this particular CCWO case, instability occurred slightly later than in the other joints after heel strike, when the stifle was extended even more than it was during heel strike, a motion pattern different to all other stifles studied. In all cases, similar to the unoperated stifles, tibial subluxation could not be documented with the exception of one TTA. In this case both caudal slippage of the femur and cranial subluxation of the tibia were documented. Excluding the two stifles showing atypical kinematics, the sagittal motion pattern of the unstable operated and unoperated stifles was visually identical.

Discussion

Our results proves both of our hypotheses, clearly demonstrating that, contrarily to what has become accepted evidence in small animal orthopedics, the CrCL insufficient stifle exhibits femoral and not tibial instability. Even following surgical treatment the motion pattern remains the same provided that, for whatever reason, the joint remains unstable. Whether the observed laxity significantly improves compared to the preoperative state in persistently unstable stifles remains unknown as we did not investigate any of the stifles more than once. This could be of particular interest when considering dynamic stabilization procedures such as TTA, TPLO or CCWO, because of their inherent biomechanical concept of force equilibration without passive restraints (11). We could hypothesize that either the forces are equilibrated providing dynamic joint stability or that the procedure failed at equilibrating the shear forces, and thus resulting in permanent instability. However the fact that in two cases with tibial osteotomy slippage of the femur either occurred to an atypical time point or instability was a mixture of femoral slippage and tibial subluxation simultaneously, suggests that even in the absence of joint stability tibial osteotomies influence stifle joint forces and may therefore indeed alter the typical motion pattern of a CrCL deficient stifle. For extraarticular lateral suture type procedures and probably for intraarticular repair procedures as well, we would expect significant reduction in joint laxity when compared to preoperative, even with persistent instability, because these procedures act as passive stabilisers to the joint. With only one stifle having an extraarticular suture type stabilisation, which contrary to our expectation seemed to have as much laxity than unoperated joints, fluoroscopic kinematography in operated stifles with lateral suture type fixation warrants further study.

Aiming for the qualitative description of the sagittal motion pattern in the canine CrCL deficient stifle only, the documented results do not allow for any conclusion why caudal slippage of the femur and not cranial subluxation of the tibia occurs in vivo, which forces are implicated and why, sometimes osteotomies of the proximal tibia fail to prevent the femur from slipping caudally. Especially the latter finding has to be investigated in the light of achieved post-operative patellar tendon angle or tibia plateau angle and state of meniscal integrity (1, 19, 30).

“Motion is relative” could one argue and adhere to the established convention of joint luxation where the distal segment defines the direction of (sub)luxation. However, even though the relative motion between the femur and the tibia remains the same regardless which point is defined as the reference, we speculate that the kinetics producing either form of motion may differ from each other. While cranial tibial sub-luxation may be explained by pull of the quadriceps muscle at the tibial tuberositiy (21), caudal slippage of the femur cannot be explained the same way. Slocum’s understanding of canine stifle instability (26), compared to a wagon parked on a hill, mimics more closely the motion pattern observed in vivo in a CrCL insufficient stifle. In case of CrCL rupture the wagon (femur) rolls downhill, along the caudally sloped tibial plateau (the hill). By reducing the slope of the hill (=TPLO) slippage of the wagon will be prevented. Nevertheless, the observation that three stifles out of five with TPLO in the present study and up to 33% of the TPLO cases reported by Kim et al. (15) remained unstable, may suggest that the simplification of the stifle’s biomechanics made by Slocum (24) may not be applicable to every dog. Being a force driven biomechanical theory (6) TTA might be even more dependent on detailed estimation of the kinetics and the resulting kinematics in the CrCL insufficient stifle. Nevertheless the relative high number of persistently unstable TPLOs and TTAs in the current study should be interpreted with caution because in some of the stifles instability might have resulted from the inability of the surgeons to accurately achieve 5 degree of tibial plateau angle or 90 degree of patellar tendon angle, respectively, and warrants thorough validation in form of a prospective study with constancy to the published surgical as well as preoperative planning guidelines for TPLO and TTA (18, 24, 25) before any definitive conclusion on the stabilizing effect of tibial osteotomies can be drawn.

The topographic anatomy of the CrCL intuitively leads to the assumption that it fixes the tibia relative to the femur. This way it is easily understandable why early reports on stifle biomechanics express stifle instability in terms of cranial drawer of the tibia (2, 10). Another explanation might be that joint instability has traditionally been defined in respect to the distal segment. In consequence, since then, any biomechanical in vitro setup was driven by the conception of tibial instability. However, the fact that even in vivo studies (16, 28) attributed the observed motion solely to the tibia is remarkable, as they measured motion both of the femur and the tibia simultaneously, and therefore all data to “see” what really happened had to be present. At the time Korvick et al. (16) performed their measurements, data analysis may not have been sophisticated enough to allow visual representation of the data. Tashman et al. (28, 29) however, could have “seen” the true motion pattern, as they used fluoroscopy, as we did. We assume that simply by convention in respect to joint luxation they reported all measured motion in terms of relative tibial motion, further strengthening the evidence of tibial instability in the literature (9, 21).

The presented data are highly biased by the way the dogs were recruited and are not representative for the biomechanical performance of the tested surgical procedures! Even though the study was performed in a prospective manner, neither all cases with complete CrCL rupture preoperatively nor all operated stifles could be investigated at follow up during the study period. This has for sure driven the selection to operated stifles with an unsatisfactory functional outcome at follow up, because we use fluoroscopy not only for scientific purposes but also as a diagnostic tool. Nevertheless, the current study’s aim was not directed at evaluating the prevalence of sagittal joint instability after surgical stabilization. Investigating surgically stabilised stifles was thought to elucidate whether surgery, especially osteotomies of the proximal tibia, might alter the sagittal motion pattern in case of persistent instability in vivo.

The degree of lameness and speed while walking on the treadmill may also have influenced the fluoroscopically documented instability. It could be speculated that severely lame dogs would bear significantly less weight on the affected limb, reducing intraarticular shear forces and therefore sagittal joint instability. With six out of six dogs in the current study having complete CrCl rupture and no stabilization performed showing the same cranio-caudal instability with the femur slipping caudally probably rejects this hypothesis. Nevertheless, we cannot completely exclude the possibility that some of the operated stifles showing no sagittal instability on fluoroscopy might have been unstable at higher speed and/or in case of reduced lameness scores. But once again, this was not one of this study’s aims, neither did we collect data which would have allowed to correlate postoperative limb function and in vivo joint instability, as it has been done by Kim et al. for TPLO cases at the stance (15).

A positive cranial drawer test was defined as inclusion criteria, whereas tibial compression test was not evaluated. We believe that cranial drawer is more sensitive for stifle instability than tibial compression test and therefore limited our clinical evaluation to this test. However, results of the tibial compression test might have provided useful information in those cases with tibial osteotomy with persistent instability in vivo, especially TPLO/TWO, and therefore should be included in future studies.

We are unable to estimate in which way the consideration of the real motion pattern of the CrCL deficient stifle, which is characterised by caudal instability of the femur, may have influenced the biomechanical concept of canine CrCL rupture and its surgical treatment in the past. But, based on the hereby reported findings, we have to question the validity of the traditional in vitro CrCL rupture models, which are driven by the idea of tibial instability and therefore do not mimic the real in vivo motion. By changing our view of the kinematics of the canine stifle in the future towards instability of the femur as the primary mechanical derangement, we might be able to develop a new, potentially more realistic understanding of the underlying kinetics involved in CrCL rupture, such as cocontraction of the gastrocnemius muscle (8).

Conclusion

Cranio-caudal stifle instability following CrCL rupture is characterized by caudal slippage of the femur, which contradicts the common understanding of cranial tibial subluxation. Following ostoeomty of the proximal tibia this motion pattern is maintained in those cases which show persistent instability. The historical focus on tibial instability following CrCL rupture might have limited our understanding of stifle kinematics in the past and should therefore be revised in the future. Overall, the unexpected high number of persistently instable stifles following surgical repair warrants close attention in future controlled studies.

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Figure 1: Uni-planar high-speed fluoroscopic unit using a standard C-Arm and a canine treadmill for gait analysis in the sagittal plane. The standard video camera of the C-arm has been replaced by a digital high-speed video camera (not shown).

Abbildung 1: Uni-planare hochfrequenz Fluoroskopie mit einem konventionellem C-Boden und einem Hundelaufband, zur Ganganalyse in der Sagittalebene. Die werkseigene Videokamera des C-Bogens wurde durch eine digitale High-Speed-Videokamera ersetz (nicht abgebildet).

Movie 1: Sagittal fluoroscopic kinematography of a Rottweiler with unilateral rupture of the cranial cruciate ligament while walking on a treadmill. Note the acute caudal slippage of the distal femur along the tibia plateau at the beginning of stance phase. Subluxation is reduced at lift of.

Film 1: Sagittale fluoroskopische Kinematographie eines Rottweilers mit einseitigem Riss des vorderen Kreuzbandes. Beachte die akute kaudal gerichtete Schubbewegung des distalen Femurs entlang des Tibiaplateaus zu Beginn der Standphase. Die Subluxation wird zu Beginn der Schwungphase wieder aufgehoben.