A review of extra-articular prosthetic stabilization of the cranial cruciate ligament-deficient stifle

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Summary
Extra-articular prosthetic stabilization techniques have been used as a method of stabilization of the cranial cruciate ligament (CrCL)-deficient stifle for decades. During extra-articular prosthetic stabilization, the prosthesis is anchored to the femur and tibia, and tensioned in the attempt to resolve femorotibial instability. The position of the anchor points of the prosthesis is crucial for restoring a normal range of joint motion and mitigating alterations in prosthesis tension during motion. Recently developed techniques offer several innovations with potential advantages such as bone-to-bone fixation, prosthetic materials with better mechanical properties, and improved isometry of the anchor points. Whether these innovations provide clinically superior results to the traditional techniques such as lateral circumfabellar-tibial suture techniques has yet to be determined.

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Introduction

Cranial cruciate ligament (CrCL) insufficiency is a common cause of hindlimb lameness in dogs that can precipitate meniscal injury and inevitably incites osteoarthritis (OA) of the stifle (1, 2). Adult, large breed dogs are most frequently affected by CrCL insufficiency with Rottweilers, Newfoundlands, and American Staffordshire Terriers being over represented breeds (3–5). Although the risk for CrCL insufficiency increases with age, many large breed dogs sustain CrCL insufficiency in young adulthood (3–5). Cranial cruciate ligament insufficiency in dogs is most commonly due to progressive, mid-substance, pathological ligamentous failure (6). Despite numerous investigations, the aetiopathogenesis of CrCL insufficiency in dogs remains unknown (7–13). Dogs with unilateral CrCL insufficiency have a 37% incidence of developing CrCL insufficiency in the contralateral stifle within a year of the initial diagnosis of the initial ligament failure (14). Cranial cruciate ligament insufficiency can also occur as a result of a traumatic injury, but traumatic CrCL rupture is less common and typically unilateral (15).

The CrCL has a complex structure and is composed of fibre bundles organized into two distinct bands: the smaller craniomedial band which remains taut in both extension and flexion, and the larger caudolateral band which is taut in extension and lax in flexion (6, 16, 17). The CrCL functions to stabilize the stifle by preventing hyperextension, cranial tibial translation, and excessive internal tibial rotation (16). The CrCL also guides the stifle through its gliding and sliding motion, which is classically described as the screw-home mechanism (17, 18). The screw-home mechanism is a term used to describe the cranial (gliding) and external rotation (sliding) motion the tibia undergoes relative to the femur as the stifle is extended (19). This phenomenon, which has been comprehensively described in the human knee, is also thought to occur in the dog's stifle (17–21).

Multiple studies have evaluated the effects of CrCL insufficiency on stifle biomechanics, kinematics, and gait (21–25). Cranial cruciate ligament deficiency alters stifle and hindlimb kinematics resulting in cranial tibial translation, increased internal rotation and adduction of the tibia especially during the stance phase of the gait cycle (22, 23). Gait and kinematics analysis of dogs with unilateral transection of the CrCL did not reveal any improvement in cranial tibial translation or coronal plane instability over a two-year study period (23). The kinematic changes that occur in the CrCL-deficient stifle alter loading of the articular cartilage and this has been postulated to be an initiating factor in the development of OA (22–24, 26). Studies mapping articular contact pressures and distribution have shown alterations in peak and mean pressures as well as in contact area in cadaveric stifles following CrCL transection (27–29). In addition, abnormal kinematics alter surface velocity and increase the plowing friction, which has been recently proposed as another mechanism to explain the relationship between abnormal articular surface interaction and the development and progression of OA (21). Restoration of normal stifle kinematics and contact mechanics should be a primary objective of CrCL insufficiency treatment (25). The multiplanar motion of the stifle coupled with the complex structure and function of the CrCL, make optimal treatment of CrCL insufficiency problematic and challenging (16, 19, 30).

Dogs suffering from CrCL insufficiency can be managed either with or without surgery. Non-surgical management involves activity modification, body weight management, and administration of analgesic and anti-inflammatory drugs (31). Non-surgical management can result in improvement of lameness in some dogs (31). In one study evaluating the efficacy of non-surgical management of dogs with CrCL insufficiency, 83% of dogs weighing less than 15 kg had improvement of lameness; whereas, lameness improved in only 13% of dogs weighing greater than 15 kg (31).

An array of surgical techniques intended to address CrCL insufficiency have been described including intra-articular stabilization, extra-articular stabilization, and tibial osteotomy techniques (32–60). Intra-articular stabilization techniques utilize autografts, allografts, xenografts, and synthetic materials to replace the incompetent CrCL (32–37). Extra-articular stabilization techniques are predicated on transiently restraining abnormal stifle motion until sufficient joint adaptation occurs to provide functional stability and improved limb function (44). Tibial osteotomy techniques alter tibial, and therefore stifle, conformation to restore functional stability to the CrCL-deficient stifle (53–59).

Two categories of extra-articular stabilization techniques have emerged: techniques using transposed autogenous structures or synthetic materials. Extra-articular techniques using autografts include procedures such as fibular head transposition, popliteal tendon transposition, and long digital extensor tendon transposition (48–51). Extra-articular stabilization techniques utilizing synthetic materials can be subcategorized to include capsular imbrication, circumfabellar prostheses, anchor, and bone tunnel techniques (38–47, 52). With numerous modifications and advancements reported over the years, extra-articular stabilization is still a technique that is commonly used today (38–52, 61). The purpose of this article was to review the clinical and experimental data published regarding extra-articular prosthetic stabilization techniques for the CrCL-deficient stifle in dogs and to offer some perspective as to the rationale behind the efficacy of these described techniques.

History

The original extra-articular prosthetic stabilization procedure described by Childers was a lateral retinaculum imbrication technique performed by placing a series of catgut sutures in a Lembert pattern in the lateral fascia of the stifle (38). Pearson modified this technique by adding a second layer of Lembert sutures to the lateral fascia as well as a series of medial imbrication sutures (39). Pearson advocated using heat-sterilized medium-weight, synthetic, non-absorbable suture material (39). An experimental study comparing Pearson's extra-articular stabilization technique and Paatsama's intra-articular stabilization technique found better clinical and post-mortem results with the extra-articular stabilization technique (32, 39, 62). In 1970, a major advancement was made by DeAngelis and Lau with the publication of the description of extra-articular stabilization by the placement of two Dacron sutures or stainless steel wires in the lateral retinacular tissues immediately caudoproximal to the fabella in the lateral head of the gastrocnemius muscle (40). The sutures were also placed through the lateral third of the patellar tendon just proximal to the insertion on the tibial tuberosity to limit cranial drawer motion, internal rotation of the tibia, and hyperextension of the stifle. The DeAngelis and Lau lateral retinacular imbrication technique was one of the last imbrication techniques to be described, but it paved the way for the circumfabellar suture techniques (40).

Nineteen seventy-five was a sentinel year in the evolution of extra-articular prosthetic stabilization techniques, with two new techniques described (41, 42). One technique, described by Hohn and Newton, involved performing a caudolateral capsulorrhaphy and imbrication of the lateral retinaculum of the stifle (41). However, according to a survey of veterinary surgeons' preferred techniques, this technique is almost never performed now (61). In 1975, Flo also described what she referred to as a modified retinacular imbrication technique, but in essence, it was the first true circumfabellar technique (42). Flo's modified retinacular imbrication technique involved placement of both medial and lateral circumfabellar-tibial sutures (42). The sutures were anchored around the fabellae in the gastrocnemius muscles and passed through a hole drilled in the tibial tuberosity (42). Securing the prosthesis in the proximal tibia was a novel concept, as all previous techniques described using the patellar tendon as the cranial suture anchorage point. The location of the hole in the tibial tuberosity was described as 6 mm distal to the proximal insertion point of the patellar tendon and 6 mm caudal to the cranial surface of the tibial tubercle (42). The stability afforded by the circumfabellar sutures was augmented by a suture placed through the lateral fabellar fascia and then passed just lateral to the patella to act as an imbrication suture (42).

Six years later, Gambardella et al. proposed a circumfabellar technique that included one lateral circumfabellar suture and two sutures placed through the lateral collateral ligament with all three sutures passing through the patellar tendon as the cranial anchorage points (43). In 1990, Brinker et al. described a modification of Flo's technique, called the three-in-one technique, in which medial and lateral circumfabellar sutures were placed as Flo had described with the exception that medial and lateral fascial imbrication was added instead of placing the third suture that was originally described by Flo (42, 44). The three-in-one, or a modification that involves placement of only one or multiple lateral circumfabellar-tibial tuberosity prostheses, are techniques still commonly performed for extra-articular stabilization of CrCL-deficient stifles in dogs (44, 61, 63–65).

Another development in extra-articular prosthetic stabilization techniques was the use of suture anchors (45). Suture anchors are used to provide secure, precise fixation of the prosthesis' origin, insertion, or both. Although the use of suture anchors had been described for other applications in dogs, Edwards et al. were the first to report the use of a human suture anchor[a] for

[a] Mitek G2 tissue anchor: Mitek Surgical products, Norwood, MA, USA

extra-articular suture stabilization of CrCL-deficient stifles in dogs in 1993 (45, 66). Suture anchors[b, c, d, e] have been developed for veterinary use, and *in vitro* studies evaluating performance have been performed in dog tibiae and femora (67–69).

Another extra-articular stabilization technique was developed by Cook and termed the TightRope CCL® [f] (47). The technique utilizes bone tunnels drilled in the femur and tibia to place a braided polyester coated polyethylene[g] suture on the lateral aspect of the stifle. The suture is passed through the tunnels and anchored to the medial aspect of the femur and tibia where the bone tunnels emerge using toggle buttons (47). Another similar transcondylar toggle system[h] has also been described (52). Although limited clinical results for these new techniques are positive, long-term clinical assessments and biomechanical studies evaluating the TightRope CCL® procedure and other similar techniques still need to be investigated (47, 52).

Prosthetic material

As the development of extra-articular prosthetic stabilization techniques has progressed, numerous factors affecting the techniques have been evaluated including the prosthetic materials, methods of sterilizing and securing the prosthesis, the locations where the prosthesis are secured, and the position of the stifle at the time the prosthesis is secured (38, 42–44, 46–47, 61, 70–74, 80–86, 92–93, 103–105). A number of materials have been proposed for use as extra-articular prostheses (38, 47, 61, 70–74). Catgut was one of the earliest suture materials used for extra-articular stabilizations (38). Polyester[i], coated caprolactam[j], and braided polyesters[k, l, m] were other suture materials that were initially advocated due to the availability of these materials in large diameter sizes (up to No. 7 metric for the polyesters) and thus a perceived increased strength. Braided material, specifically coated caprolactam, has been implicated in the formation of draining tracts (70). In one study, draining tracts formed in as many as 21% of cases seven to 280 days after implantation of an extra-articular braided suture material (70). *Staphylococcus aureus* was the most commonly isolated bacteria in these cases (70). Resolution of the draining tracts occurred after removal of the suture in all cases; however, lameness resolved in only 65% of the dogs after suture removal (70). The soaking of braided suture material in chlorhexidine solution before implantation has been reported to decrease the frequency of draining tracts (75). Nevertheless, the use of braided suture materials has been generally supplanted by the use of monofilament materials in circumfabellar techniques (61). Monofilament suture materials are infrequently associated with the development of draining tracts; however, No. 5 metric nylon[n] and polypropylene[o] are the largest diameter materials readily available (75). For this reason, larger diameter monofilament materials such as monofilament nylon fishing line and monofilament nylon leader material have been used for extra-articular stabilization (71, 72). In a study comparing No. 5 metric polypropylene, No. 7 metric multifilament polyester, and monofilament nylon leader material, the monofilament nylon leader material was able to maintain a significantly greater percentage of static tensile load compared to the other materials tested (71). A similar study comparing monofilament nylon leader materials and monofilament nylon fishing materials found that monofilament nylon leader material[p] sterilized with ethylene oxide had the least elongation and most strength preservation in comparison to the other materials tested (72). Stainless steel wire has also been advocated for use as a prosthesis for extra-articular stabilization of the CrCL-deficient stifle (73). A retrospective study evaluating dogs that underwent circumfabellar-tibial tuberosity extra-articular stabilization with stainless steel wire found that 93% of dogs had one or more breaks in the wire six month following surgery (76). Other materials, such as an ethylene tetrafluoroethylene tie, nylon band, polyvinylidene fluoride, braided polyester coated polyethylene sutures[q, r], and tape[g], have been proposed for use in extra-articular stabilization; however, most of these materials are not routinely used (47, 52, 61, 74, 77–79).

Materials such as nylon fishing line and monofilament nylon leader material must be sterilized prior to implantation. Several studies have been done to evaluate how different sterilization methods affect the mechanical properties of these materials (71, 72, 80). Steam-sterilization, including one cycle and five cycles in an autoclave, as well as ethylene oxide sterilization have been the major methods evaluated. In *in vitro* mechanical studies, ethylene oxide sterilization was found to conserve the material properties and handling characteristics of monofilament nylon leader material better than steam sterilization (71, 72, 80). Steam sterilization undesirably increases elongation and decreases stiffness of both fishing line and leader material (80).

Securing the loop of material used as an extra-articular prosthesis is another variable that has received considerable attention. Knotting the material or using a crimp clamp are the two methods commonly utilized to secure extra-articular prosthesis (42–44, 46, 47, 72, 80–86). Knotting the material is the traditional method of securing the extra-articular prosthesis and several types of knots have been described for this use including square knots, clamped square knots, sliding half-hitch knots, sur-

[b] BoneBiter: Innovative Animal Products Inc., Rochester, MN, USA
[c] IMEX Veterinary Inc., Longview, TX, USA
[d] Securos Inc., Charleston, MA, USA
[e] FlexiTwist: Innovative Animal Products Inc., Rochester, MN, USA
[f] Tightrope CCL Technique: http://www.innovatiLveanimalproducts.com/tightrope.php
[g] Fibertape: Arthrex Vet Systems, Naples, FL, USA
[h] Transcondylar Toggle System: Securos Inc., Charleston, MA, USA (52)
[i] Ethibond: Ethicon, Somerville, NJ, USA
[j] Vetafil: S Jackson Inc, Washington, DC, USA
[k] Polydek: Deknatel, Riverfalls, MA, USA
[l] Mersilene: Ethicon, Somerville, NJ, USA
[m] Ticron: Davis & Geck, Danbury, CT, USA
[n] Ethilon: Ethicon, Somerville, NJ, USA
[o] Prolene: Ethicon, Somerville, NJ, USA
[p] Mason Hard Type Monofilament Nylon Leader Material: Mason Tackle Co., Otisville, MI, USA
[q] OrthoFiber: Securos Veterinary Orthopedics, Fiskdale, MA, USA
[r] Fiberwire: Arthrex Vet Systems, Naples, FL, USA

geon's knots, and self-locking knots (82–84). *In vitro* studies have demonstrated that the type of knot can influence the structural properties of some suture material loops (80, 83). For instance, when 27 kg monofilament nylon leader material was knotted with a surgeon's knot the suture's stiffness was reduced by 27% and when the same material was knotted with a sliding half-hitch the suture's load-to-yield was reduced by 20% (83). Knot type, however, did not affect the stiffness or load-to-yield of No. 5 metric nylon or polybutester (83). A square knot in which the first throw is clamped to maintain loop tension as the rest of the knot is tied has been evaluated for a number of suture materials with no detrimental effects to the structural properties of 27 kg monofilament nylon fishing line, No. 5 metric nylon, or No. 5 metric polybutester (80, 83). Conversely, clamping the first throw of a square knot in monofilament nylon leader material has been shown to increase failure load by two percent and stiffness by 16%, and to decrease elongation by 12% (80). Thus according to Huber et al., clamping the first throw of a square knot of leader material to aid in maintaining loop tension is preferable to securing the same material with a sliding half-hitch to maximize the suture's structural properties (83).

An alternative to knotting the prosthesis is securing the loop with a crimp clamp (72, 84–86). An *in vitro* biomechanical study comparing sliding half-hitch knotted monofilament nylon leader material to the same material secured with a crimp clamp demonstrated that monofilament nylon leader material secured with a crimp clamp had significantly less elongation, greater failure load, and the potential to achieve higher initial tension than the knotted prosthesis in single load-to-failure and cyclic tests (85). Vianna and Roe had similar findings when evaluating monofilament nylon leader material secured with either a crimp clamp or a clamped square knot; although the clamped square knot resisted a greater peak load, the leader material secured with a crimp clamp had less elongation and more stiffness in both static and cyclic tests when compared to the knotted leader material (84). Premature crimp clamp slippage, as deemed by significant cranial drawer motion and abnormal radiographic location of the crimp clamp, was found to occur in eight percent of 110 cranial cruciate ligament deficient stifles stabilized with a circumfabellar-tibial monofilament nylon suture (87). Crimp clamp placement does require additional equipment and is currently only commercially available for use with specific prosthetic materials. The loop configuration of the prosthetic material may be an additional factor affecting its performance (106). In a mechanical study, the strongest configuration, with a significantly higher mean ultimate load and load at yield, was the interlocking loop configuration (106). The double strand group with uneven loop length performed very poorly, with significantly lower mean stiffness and ultimate load than all of the single strand groups (106).

In most cases, the tension of the prosthetic suture is not conserved for longer than six to eight weeks post-implantation (76). The most common mechanisms of prosthesis failure are elongation or rupture, but pullout from the anchorage site has also been reported (76, 81). Failure of the prosthesis by loosening may occur if the prosthesis is not anchored properly. Circumfabellar prostheses should be placed through the femorofabellar ligament to anchor the prostheses around the fabella. A common mistake is to anchor the prosthesis caudal and distal to the fabella (75). The type of prosthetic material and the method used to secure the prosthesis effects the mechanism of failure. Knotted or crimped nylon leader materials are more likely to fail by elongation, while nylon leader material secured by a bone anchor may predispose the prosthesis to failure by rupture (69, 80). Prosthetic materials with a high load-to-failure and an increased resistance to elongation such as braided polyester coated polyethylene materials[g, q, r] are more prone to failure by anchor pullout rather than prosthesis elongation or rupture (69). It has been suggested that maintaining the initial tension of the prosthesis for two months should be sufficient to allow recovery and improved function. However, some dogs may need more prolonged stabilization to allow for joint adaptation, to regain satisfactory limb function, and prevent postoperative meniscal injuries which may necessitate additional surgery (75, 88).

Biomechanics

In addition to the mechanical evaluation of the extra-articular prostheses, several biomechanical aspects of extra-articular stabilization techniques have been investigated. The lateral circumfabellar-tibial suture technique is the most widely used extra-articular stabilization procedure for the CrCL-deficient stifle (64, 89). The lateral circumfabellar-tibial suture technique is frequently performed by placing a prosthesis around the lateral fabella and through a hole drilled in the tibial tuberosity. After passing the prosthesis under the patellar tendon, the ends of the suture are secured with a knot or a crimp clamp on the lateral aspect of the joint (▶Fig. 1) (64). Variations of this technique include passing the suture through two bone tunnels in the tibia or through a small hole drilled in the lateral fabella (90, 91).

The lateral circumfabellar-tibial suture technique is intended to resolve cranial tibial thrust by maintaining the tension applied to the prosthesis at the time of implantation. Clinical guidelines regarding how to tighten the prosthesis and on the amount of tension necessary to stabilize the stifle are unclear. It has been suggested that to eliminate cranial drawer, the tibia should also be externally rotated while the stifle is held at a weight-bearing angle during the application of an extra-articular prosthesis (86, 92, 93). The use of pointed reduction forceps[s] have been described for this purpose (92). Self-retaining tensioner devices can be also used to tension the prosthesis and test for cranial drawer before tying the knot or securing crimps (94). A recent cadaveric study investigated whether the joint angle at which the prosthesis is secured effects prosthetic tension through a full range of stifle motion for circumfabellar-tibial suture and anchor techniques (95). Based on the results of this study, tightening the suture at about 100 degrees of stifle flexion provided sufficient joint stabilization and

[s] AO pointed reduction forceps: Synthes, West Chester, PA, USA

uniform prosthetic tension throughout the full range-of-motion (95). These guidelines should be considered cautiously as cadaveric studies cannot replicate the complex *in vivo* motion of the joint. Guidelines regarding suture tension are also unclear, probably because other variables such as fixation points (soft tissue versus bone) and mechanical properties of the prosthesis would affect long-term tension of the prosthesis. Although complete elimination of cranial drawer motion might be deemed desirable because it is an abnormal motion resulting from the CrCL insufficiency, excessive suture tension may be more detrimental than minor joint instability (23). In a retrospective clinical study, dogs which had satisfactory functional outcomes had increased cranial drawer motion and greater stifle range-of-motion at a mean follow-up time of 34 months compared to dogs which had unsatisfactory outcomes (96). Excessive suture tension may predispose to early failure of the suture, decrease range-of-motion and abnormal intra-articular pressure. An *ex vivo* biomechanical study which investigated the effects of extra-articular stabilization upon the contact mechanics of the lateral compartment of the stifle found that excessive extra-articular prosthesis tension caused increased lateral compartmental pressures (94). The effect of an overtightened extra-articular prosthetic suture may be more relevant in smaller dogs and in non-weight-bearing conditions as it was shown that axial compression redistributed the abnormal pressure distribution to both compartments (94).

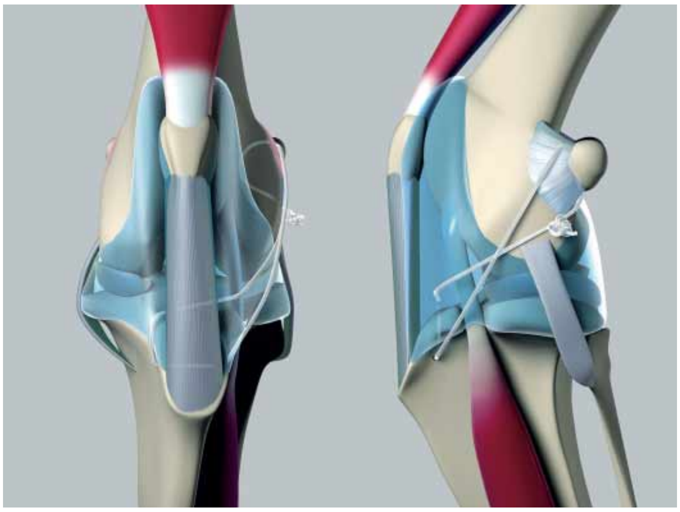

Fig. 1 Craniocaudal and lateral illustrations of a stifle with a lateral circumfabellar-tibial suture technique. Note that a small portion of the 'extra-articular' suture is within the joint.

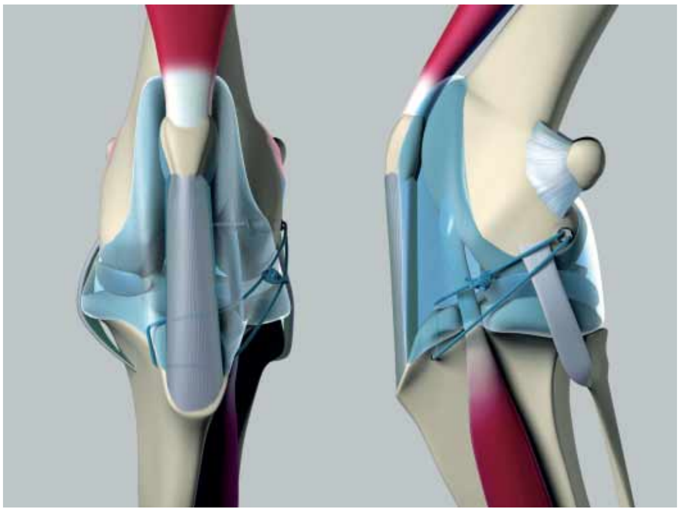

Fig. 2 Craniocaudal and lateral illustrations of a stifle with an anchor technique.

Joint stability following extra-articular stabilization techniques has been investigated in cadaveric models (46, 97). Harper et al. evaluated cranial-caudal femoral displacement following three variations of the lateral circumfabellar-tibial suture technique and a lateral autograft technique using a material testing machine to apply loads to the femur ranging from -65 N (caudal drawer) to 80 N (cranial drawer) (46). The authors did not find any significant differences in displacements between stifles stabilized with the circumfabellar-tibial suture technique and intact stifles (46). Femoral displacement was also evaluated with the circumfabellar suture attached to three separate tibial points (tibial crest, cranial and caudal to the extensor groove). The tibial crest position resulted in the least displacement supporting its use when combined with the circumfabellar placement. The lateral graft technique evaluated by Harper et al. and Snow et al. incorporates the fascia lata into an autograft used as an extracapsular graft (46, 97). Snow et al. modified the technique by using a referencing instrument to find the relative isometric location for the fascia lata translocation technique (97). Both studies evaluated the static stability immediately after implantation (46, 97). Future studies should investigate the stability of the extracapsular stabilization technique after cyclic fatigue. More importantly, further studies are warranted to determine if these techniques restore normal joint kinematics.

Despite positive clinical results, extra-articular stabilization techniques do not achieve the optimal treatment goal of restoration of normal stifle kinematics to the CrCL-insufficient stifle (81, 98–101). A radiographic study showed that CrCL-deficient stifles stabilized with the De Angelis and Lau lateral retinacular stabilization technique had an abnormal instant centre of motion (18, 40). Furthermore, *ex vivo* evaluation of the three-dimensional kinematics of the CrCL-deficient stifle after stabilization with the modified retinacular imbrication technique found that there was a 30 degree decrease in stifle flexion and increased external rotation and abduction of the tibia (42, 102). Complete elimination of tibial rotation by the extra-articular prosthesis is undesirable since a small degree of

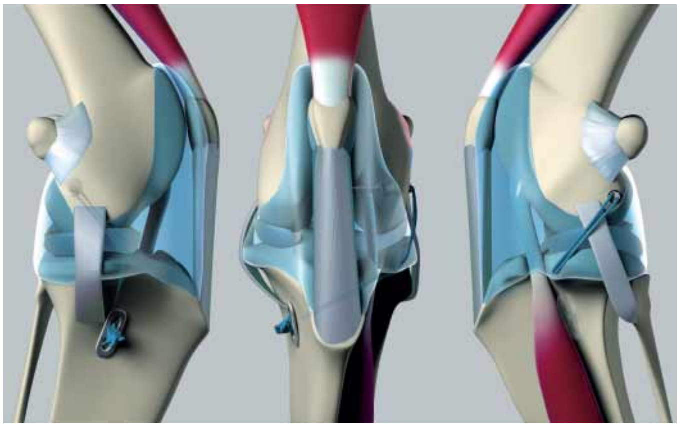

Fig. 3 Medial, cranio-caudal, and lateral illustrations of a stifle with a modified anchor technique.

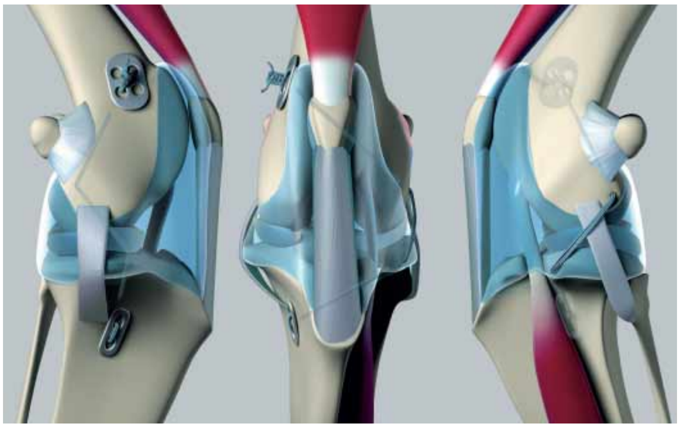

Fig. 4 Medial, cranio-caudal, and lateral illustrations of a stifle with the Tight-rope CCL technique.

axial rotation is a normal part of stifle motion (16, 20). These studies highlight the limitations of the extra-articular stabilization techniques in restoring normal kinematics and contact mechanics of the CCL-deficient stifle (18, 102).

Another variant of extra-articular stabilization technique utilizes bone anchors and tunnels to fix the prosthetic suture across the stifle. Following a standard approach as for the circumfabellar suture technique, a bone anchor is placed in the caudal aspect of the femoral condyle distal to the lateral fabella. The suture is passed through one or two tunnels in the tibia and tied laterally (►Fig. 2). Variations of this technique include using multiple anchors, a single or double tibial tunnel, or a toggle button placed on the medial aspect of the tibia (►Fig. 3) (79). One of the proposed advantages of this technique is to allow more isometric suture placement than other extra-articular techniques. In a radiographic study, Roe et al. defined sagittal plane isometric extra-articular suture placement points for the femur and tibia (103). Hyman et al. and Hulse et al. found similar isometric points by measuring the change in strain of a suture attached to different femoral and tibial anchorage sites (104, 105). Both methods for determining the isometric points had limitations which were discussed in a recent study by Fischer et al (95). In this study, the authors found that neither the circumfabellar suture nor the anchor techniques provided a constant suture tension while moving the stabilized stifle through a full range-of-motion (95). The significant increase in tension (>100 N) measured with the joint in flexion could predispose to over-constraint of the joint, premature failure of the prosthesis, or failure of the bone anchor (67–69, 81, 95, 103). Cadaveric studies have demonstrated that higher acute load-to-failure of the anchor occurs when the anchor is placed in the caudolateral aspect of the lateral femoral condyle (68, 69). These results have been corroborated in a retrospective clinical study (81). Although an isometric point has been described for the tibia, suture anchors are used infrequently to secure extra-articular prostheses to the tibia (81, 103). The prosthesis is generally secured through a hole drilled in the tibia positioned within or just caudal to the proximal aspect of the groove of the long digital extensor tendon (103).

The term isometry should be used cautiously when referring to anchorage points of prostheses for CrCL reconstruction and stabilization. The origin and insertion of the CrCL are not isometric, explaining why some of the fibres become lax at certain angles of stifle flexion and extension (6, 16, 17). Thus, extra-articular suture anchor points cannot be isometric as the stifle is not a pure hinged joint (17–19). The anchorage points used for extra-articular stabilization may be better defined as 'quasi-isometric' because these points aim to be as close as possible to isometric. Cognizant of this limitation, the goal of the stabilization technique shifts to a 'physiological isometry' rather than a geometrical isometry. Physiological isometry allows for some minor elongation, as long as the deviation throughout the range-of-motion reproduces that of the native CrCL. Physiologic isometry should approximate normal joint kinematics and may vary between dogs. In considering physiological isometry, the material properties of the prosthesis cannot be ignored. Anchor points of stiffer prostheses such as FiberTape[g], FiberWire[r], and OrthoFiber[q] should more closely approximate isometry than less stiff prosthetic materials because the stiffer prosthesis will generate much higher forces if isometry is poor. Re-establishing normal joint kinematics remains the ultimate goal of any CrCL stabilization technique; however, the 'quasi-isometry' of the extra-articular prosthetic anchor points may achieve a physiologic isometry that can result in a good functional outcome (47, 81).

Creep, stress-relaxation, ultimate load-to-failure and other material properties of the prosthesis used for extra-articular stabilization, and the properties of the tissues to which the prosthesis is anchored (bone or soft tissue) are additional variables that

Table 1 The table summarizes some of the most important clinical studies on extra-articular stabilization techniques that have been published in veterinary literature.

Reference & level of evidence	Technique	Study type & follow-up	Subjects evaluated	Force plate evaluation	Owner assessment	Physical examination	Radiographic examination
Jevens DJ et al. (99) Level 3	Modified retinacular imbrication technique (MRIT)	Experimental Randomized 20 weeks	6 dogs	Yes	No	No	No
Budsberg SC et al. (98) Level 3	MRIT using hard type monofilament nylon leader material	Prospective Non-randomized 7-10 months	9 dogs	Yes	No	No	No
Conzemius MG et al. (100) Level 3	Lateral circumfabellar tibial suture technique (LS)	Prospective Non-randomized 6 months	47 dogs	Yes	No	No	No
Moore KW et al. (97) Level 4	LS	Retrospective mean: 20.6 ± 15.1 months	58 dogs	No	Yes	Yes	No
Guenego L et al. (80) Level 4	Suture anchor technique	Retrospective mean: 18 months	42 dogs	No	Yes	Yes	Yes
Elkins AD et al. (2) Level 4	LS	Retrospective mean: 23 months (range: 6 - 132)	58 dogs	No	Yes	Yes	Yes
Au KK et al. (107) Level 3	LS	Prospective Non-randomized 24 months	35 dogs	Yes	No	No	Yes
Cook JL et al. (47) Level 2	Tightrope CCL technique	Prospective 6 months	24 dogs	No	Yes	Yes	Yes

can influence the effectiveness of circumfabellar-tibial or more isometric suture anchor or bone tunnel techniques. One of the potential advantages of the TightRope CCL® (▶Fig. 4) is the utilization of a stiffer prosthesis. In a recent study, the materials properties of FiberTape[g] were compared to four different commercially available extra-articular prostheses: No. 5 metric FiberWire[r], 36 kg test monofilament nylon leader line, OrthoFiber[q], and braided polyethylene fibre[t] (47). The authors found that FiberTape[g] had significantly less cyclic displacement than the other materials tested (47). FiberTape[g] was significantly stiffer and had significantly greater yield loads and ultimate load-at-failure than the other prostheses (47). These results are supported by an *in vitro* biomechanical study by Burgess et al. which compared FiberTape[g], No. 2 metric FiberWire[r], OrthoFiber[q], and 36 kg test monofilament nylon leader line[p] (107). FiberTape[g] was determined to have the greatest stiffness, greatest ultimate load at failure, and least elongation of the materials tested (104). The superior mechanical properties of FiberTape[g] may have advantages with respect to stifle stability in techniques that rely on soft tissue fixation. However, the relatively stiff FiberTape[g] puts the joint at higher risk if the prosthesis is over-tightened or if the isometry of the fixation points is poor (94). Instances of poor application of the stiff prosthesis may detrimentally increase joint forces or cause premature failure of the extra-articular stabilization (94).

[t] Braided polyethylene fiber used in LigaFiba Iso Toggle System: Jorgensen Laboratories, Loveland, CO, USA

Clinical results

There has been a scarcity of evidence-based literature thus preventing direct comparisons of the multitude of extra-articular stabilization techniques that have been developed (30) (▶Table 1). Most clinical studies evaluating extra-articular stabilization techniques, with the exception of a few non-randomized prospective studies, are retrospective in nature with subjective data assessments (2, 81, 98–101). Despite this deficiency in the literature, extra-articular stabilization techniques have generally positive reported clinical results (81, 98–101). Moore and Read reported the retrospective evaluation of 40 dogs approximately 20 months after using No. 5 metric polypropylene or 37 kg test monofilament nylon leader material in a circumfabellar-tibial tuberosity technique to achieve extra-articular stabilization of CrCL-deficient stifles (98). Ninety percent of the owners were satisfied with the treatment result based on telephone questionnaire (98). On follow-up examination of 11 of the 40 dogs, there was a 12 degree loss of flexion in the stabilized stifle; however, the majority of the dogs' lameness improved following surgery (98). Improvement was also noted in a prospective clinical study performed in 12 dogs with unilateral CrCL injuries (99). Force plate data was used as an objective measure of limb function. Prior to surgery, peak vertical force, associated impulses, and weight distribution were significantly less in the affected hindlimb than in the contralateral limb without stifle pathology (99). Dogs were examined again seven to 10 months following extra-articular stabilization using monofilament nylon leader material and excision of damaged menisci (99). At the time of follow-up evaluation, peak vertical force, vertical impulse and weight distribution had increased significantly in the operated limb in all dogs (99). Despite the fact that three of the dogs had palpable drawer movement in the stabilized stifle, there were not any significant differences detected in the ground reaction forces measured between the limbs that had undergone extra-articular stabilization and the contralateral, normal hindlimbs (99). Additionally, an experimental study by Jevens et al. demonstrated that normal dogs which had a unilateral transection of the CrCL followed by a modified retinacular imbrication technique using monofilament nylon leader material did not have any significant difference in peak vertical force and vertical impulses at 20 weeks after extra-articular stabilization as compared to preoperative values in the same limb (100). In this study, the preoperative CrCL-intact stifle was used to define normal limb function rather than using the contralateral hindlimb due to a significant increase in peak vertical force in the contralateral hindlimb at all times points measured after CrCL transection (100). The redistribution of vertical forces in dogs with chronic unilateral hindlimb lameness may indicate that the use of data from the preoperative limb more accurately characterizes normal limb function in comparison to data from the contralateral hindlimb after unilateral CrCL transection and stabilization (100). Careful consideration of how individual studies define 'normal' is of particular importance when interpreting and comparing results between studies. Additionally, the inclusion or exclusion of postoperative rehabilitation is another variable that affects clinical outcome as documented by Marsolais et al. and others (108, 109). In a prospective clinical evaluation of the effect of surgical technique on limb function performed in Labrador retrievers with unilateral CrCL insufficiency and medial meniscal injuries, the force plate parameters of dogs which had extra-articular stabilization using monofilament nylon leader material were not significantly different to those of dogs that had tibial plateau levelling osteotomies at two and six months following surgery (101). All dogs in this study had medial meniscal injuries and the damaged meniscus was either partially or completely excised, but only dogs that had extra-articular stabilization underwent aggressive postoperative physical therapy. Peak vertical force was 93% and vertical impulse was 96% of normal values in the limbs of dogs that had extra-articular stabilization at six months following surgery. Peak vertical force and vertical impulse were both 96% of normal in the limbs of dogs that had tibial plateau levelling osteotomies at six months following surgery. Although only 40% of dogs that underwent extra-articular stabilizations were considered to have normal limb function based on the author's definition, an even smaller percentage (34%) of the dogs that had a tibial plateau levelling osteotomy (TPLO), were considered to have normal limb function six months following surgery. Thus in this study the clinical results obtained following extra-articular stabilization were not found to be significantly different to results obtained in dogs which underwent a TPLO (101).

A recent study compared the short- and long-term functional and radiographic outcome of CrCL-deficient dogs treated with identical physical rehabilitation regimens and either TPLO or lateral circumfabellar-tibial suture (110). Peak vertical force and vertical impulse measured with force plate analysis at three, five and seven weeks, and at six and 24 months postoperatively were used to compare the functional outcome. Radiographic evaluation of osteoarthritis progression was done at 24 months postoperatively. In both treatment groups, peak vertical force increased from preoperative to 24 months, but the differences between the groups were not significant at any time point (110). This study confirmed the results of Conzemius et al. where similar limb function was observed in dogs after TPLO or lateral circumfabellar-tibial suture (101, 110). A criticism of that study was the use of early postoperative physical rehabilitation for dogs treated by lateral circumfabellar-tibial suture compared with dogs undergoing TPLO that had exercise restriction for six to eight weeks after surgery (101). Despite elimination of this confounding factor by using identical rehabilitation protocol for both groups, no difference was found between dogs treated with TPLO and lateral circumfabellar-tibial suture (110). This result should be interpreted carefully as dogs in the lateral circumfabellar-tibial suture group were significantly lighter than dogs in the TPLO group (110). It is possible that dogs of larger size treated with lateral circumfabellar-tibial suture would have had worse outcome.

Guenego et al. reported the retrospective clinical and radiographic results of 42 large or giant breed dogs with CrCL insufficiency treated with a lateral extra-articular braided polyester suture and bone anchors (81). The suture was secured using a suture anchor[j] placed in the lateral femoral condyle and passed through two bone tunnels in the proximal tibia located just cranial to the groove of the long digital extensor tendon. Twenty-one percent of the suture anchors had pulled out of the femoral condyle at the end of the 18 month study period; however, lameness was only reported in two of these dogs (81). Anchor pullout was frequently associated with imprecise anchor placement in the femoral condyle, occurring most often in cases of chronic CrCL rupture. Anchor pullout was less often a problem if the anchor was placed in the caudolateral aspect of the lateral femoral condyle, just cranial to the fabella (81). Two dogs required a revision surgery after the suture broke adjacent to the femoral anchor (81). No draining tracts were reported despite the use of braided suture material (81). The progression of radiographic signs of osteoarthritis was noted in all cases irrespective of the isometry of the suture anchorage points (81, 103). A retrospective radiographic study by Elkins et al. evaluated 58 dogs after extra-articular stabilization using a monofilament nylon suture[n, p] placed around the lateral fabella and through a single hole made in the cranial edge of the tibial tuberosity at the level of the insertion of the patellar tendon (2). Radiographic follow-up ranged from six to 132 months with a mean of 23 months (2). Although dogs weighing less than 15 kg had a lesser degree of osteophyte formation and returned to weight-bearing faster than dogs weighing greater than 15 kg, extra-articular stabilization did not mitigate progression of the radiographic signs of OA in either group (2). Once more this outcome implies that although potentially beneficial clinically, extra-articular stabilization is not a panacea for CrCL-insufficiency.

The clinical outcome of TightRope CCL® has been recently reported in a prospective study comparing TightRope CCL® to TPLO (47). The authors evaluated these techniques by comparing subjective measurement of cranial drawer and cranial tibial thrust at eight weeks and six months after surgery, and limb function using a validated client questionnaire (47). Subjective assessment of radiographic progression of OA was also performed at two and six months after surgery. The TightRope CCL® technique resulted in outcomes which were not different than TPLO at six months after surgery. Major complication rates were not significantly different between TightRope CCL® (12.5%) and TPLO (17.4%) (47). Complications of TightRope CCL® include implant failure, infection, meniscal tear and seroma. Based on these results the authors (47) recommended TightRope CCL® technique for medium, large, and giant breed dogs with CrCL deficiency (47). The results of a multicenter study on TightRope CCL® has been recently presented, reporting 93.9% of dogs with good to excellent outcomes and a 9.2% major complication rate (111). The results of this study should be interpreted carefully because of the study's limitations (111). The outcomes and follow-up rechecks were variable among dogs and generally based on the evaluation by the attending surgeon.

Conclusion

There are many variations of extra-articular stabilization that are routinely used to treat the CrCL-deficient stifle and facilitate clinical improvement (40, 42, 45, 64, 65, 101). To date, no specific technique has been shown to yield superior results for treatment of the CrCL-deficient stifle (30). Future studies should be directed toward outlining the virtues and inadequacies of the current techniques to establish a foundation for a better understanding of how each technique effects stifle and limb function. *In vivo* kinematic analysis has been performed in human patients with anterior cruciate ligament rupture and anterior cruciate ligament deficient-knees treated with different techniques to gain a better understanding of the effects on knee stability, function, and the development of OA (25, 112–116). Similar *in vivo* three-dimensional kinematic studies might be useful if performed in dogs with CrCL-deficient stifles stabilized with different treatment techniques. There are also vast individual variations and other facets to consider such as differences in activity level, degree of periarticular fibrosis, presence of meniscal pathology and meniscal treatment that would likely alter the efficacy of any extra-articular stabilization technique in a given dog.

Conflict of interest

The author Antonio Pozzi received funding from Arthrex Vet Systems and Kyon for research projects.

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