BIOMECHANICAL STUDIES OF CANINE STIFLES WITH TORN CRANIAL CRUCIATE LIGAMENTS AND AN EVALUATION OF AN INTRA-ARTICULAR REPAIR

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Abstract

The direct and indirect effects of cranial cruciate ligament ruptures on stifle joint stability have been well documented. In most cases of cranial cruciate ligament rupture, it is advisable to have corrective surgery. Since the recognition of the high frequency of cranial crucial ruptures, there has been a large number of surgical techniques devised in order to return stability to the stifle. Even so, in most instances the effectiveness of these repair techniques has only been subjectively evaluated.

Consequently, the goals of this research were to present an accurate objective procedure for evaluating methods of joint repair and to utilize this method to evaluate an intra-articular method of cranial cruciate ligament replacement called the over-the-top technique. The objective procedure utilized for determining the effectiveness of joint surgery, involved the use of instantaneous centres of rotation. The technique modified the original Rouleaux method by replacing the vectors with smooth fitting curves, in order to reduce the error in locating the instantaneous centre of rotation. The instantaneous centres at different angulations were compared between normal (control), cranial cruciate ruptured, and cruciate repaired stifles.

The instantaneous centre of rotation of the injured stifle was found to be significantly caudal and proximal, relative to the instantaneous centre of the normal joint. There was no significant displacement of the instantaneous centre in the repaired stifle compared to the instantaneous centre of the normal stifle. This indicated that injured stifle was biomechanically abnormal with significant craniocaudal and proximodistal laxity, but the over-the-top surgery did restore the biomechanics of the joint to within normal limits.

The instantaneous centre of rotation position at the different angulations was found to be at or near the articular surface of the femur in the normal stifle

joint. The motion at the point of contact in the normal stifle was predominantly rolling or tangential to the articular surface. Therefore, minimal frictional force was created. The injured stifle showed a caudal and proximal displacement of the instantaneous centre of rotation away from the articular surface at the different angulations. This indicates a predominantly sliding motion in the stifle joint. Also, the movement at the contact po nt in the injured stifle was compressing or separating the joint, depending on rection of the velocity vector.

The repair of the cranial cr ate ligament displaced the position of the instantaneous centre of rotation tow the articular surface of the femur, but the shift was not complete. Theref iding was occurring in the repaired joint, but not as much as was und i d joint. The surgery did eliminate the compressive and/or separative aused by the injury in most angles of flexion.

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1. GENERAL INTRODUCTION

1.1 Historical review

Since the cranial cruciate ligament (CCL) in the dog has the same anatomical features as that of man (1), much anatomical and functional information about the human cranial cruciate can be related to the cranial cruciate of the dog. Galen first described the cranial cruciate ligament of man in 170 AD but there was at that time little interest in the ligament. It was not until 1850 that Stark described rupture of the ligament. Eight years later Mayo Robson performed the first repair on a human cranial cruciate ligament (2).

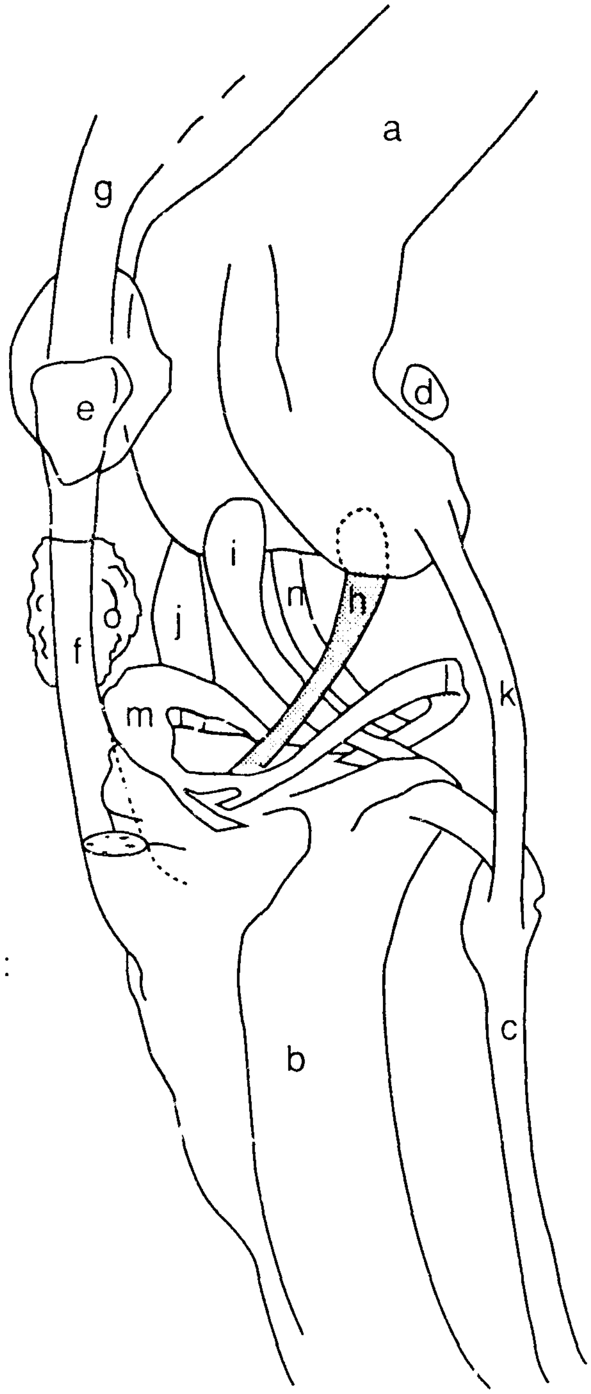
The functional significance of the cranial cruciate ligament in the stifle joint was first acknowledged by Fick (3). Hey Groves (4) later reported movement of the joint changed the tension of the cranial cruciate ligament and the cranial cruciate ligament prevented the tibia from being displaced cranially relative to the femur (3). Three years earlier Hey Groves (5) had reported on a cranial cruciate ligament reconstruction technique utilizing fascia lata. This procedure served as a basis for modern methods of intra-articular ligamentous reconstruction (2).

Carlin, in 1926, was the first to describe the problem of cranial cruciate ligament rupture in the dog. Paatsama (6) was to discuss the clinical aspects first on canine cranial cruciate ligament ruptures stating the cranial cruciate ligament was the most commonly injured ligament of the stifle joint in dogs (6). The cranial cruciate ligament has also been reported as the most injured ligament of the knee in man (7). Paatsama then went on to consider options for surgical treatment. Paatsama modified Hey Groves' (5) cruciate reconstruction technique using fascia lata, adapting it for use in the dog. Since that time, numerous procedures have been introduced, primarily directed toward control of the instability that loss of the ligament produces.

It was not until 1979, when Arnoczky et al. reported a cranial cruciate ligament substitution procedure (over-the-top technique) that modified a method used to replace this cruciate ligament in man (8) that duplication of the precise anatomy, location, and tension of the original ligament was attempted, with intent to reproduce the biomechanics of normal joint motion. This paper showed functional measurements within the normal limits after the cruciate repair. It was the goal of this work to evaluate this over-the-top procedure by comparing the movement of the damaged and repaired stifle with the movement of a normal stifle, using the instantaneous centre of rotation.

1.2 Anatomy of stifle joint

The stifle is a complex synovial joint found at the junction of the two longest bones of the body, the femur and tibia (Figure 1). The articular structures of the femur are the lateral and a medial condyles separated by an intercondylar notch. These condyles are roller shaped and articulate, in part, directly with the flattened medial and lateral condyles on the tibia. Most of the surfaces of the femoral condyles articulate with medial and lateral biconcave, C-shaped fibrocartilages called menisci, which open axially on the proximal surface of the tibia. The medial meniscus is located on the medial tibial condyle while the lateral meniscus is found on the lateral condyle of the tibia. These menisci attach to the articular surfaces of the tibia and femur via meniscal ligaments and act to produce congruence between the articulating surfaces of the femur and tibia (9).



(Illustrations based on Adams, D.R., Canine Anatomy, Iowa State University Press, 1986)

Figure 1

Anatomy of stifle joint including:

a. femur
b. tibia
c. fibula
d. lateral fabella
e. patella
f. patellar ligament
g. patellar tendon
h. cranial cruciate ligament
i. caudal cruciate ligament
j. medial collateral ligament
k. lateral collateral ligament
l. lateral meniscus
m. medial meniscus
n. meniscofemoral ligament
o. infrapatellar fat body

Located abaxial to menisci are the lateral collateral and the medial collateral ligaments. They aid in the stabilization of the stifle against valgus and varus movement. Axial to the menisci, two ligaments cross the joint from the femur and attach to the tibia. These are the cranial and caudal cruciate ligaments. The caudal cruciate ligament attaches to the lateral aspect of the medial femoral condyle and inserts on the lateral aspect of the popliteal notch of the tibia. The cranial cruciate attaches to the caudomedial aspect of the lateral femoral condyle and inserts on the cranial intercondylar area of the tibia.

The tibial tuberosity is a large eminence at the cranioproximal extremity of the tibia and is the site of insertion of the patellar ligament. The patellar ligament is a continuation of the tendon of insertion of the quadriceps femoris muscle. This ligament extends from the patella to the tibial tuberosity. The patella is the largest sesamoid bone in the body and has mechanical and protective functions in the stifle. Three smaller sesamoid bones are also situated in the area of the stifle joint. These include two fabellae caudal to the stifle, situated at the origins of the heads of the gastrocnemius muscle on the medial and lateral condyles. The third sesamoid bone is in the tendon of the m.popliteus (9).

1.3 Anatomy of cranial cruciate ligament

The cranial cruciate ligament is the focus of this work. A more detailed discussion of the anatomical description of this ligament is presented. The femoral attachment site of the cranial cruciate ligament is a fossa on the caudomedial aspect of the lateral femoral condyle. The cranial cruciate ligament extends diagonally from its femoral attachment, in a craniomedial direction, across the joint to a fossa in the cranial intercondyloid area of the tibia (10). This tibial attachment site is wider and stronger than the femoral attachment. As the ligament extends across the joint it twists on itself in a lateral helical manner (10, 11).

Both attachment sites of the cranial cruciate ligament consist of interdigitations of the collagenous fibres of the ligament with the periosteal fibres (12) of the femoral and tibial bones. At these attachments are transition zones of mineralized fibrocartilage which serves to spread the attachment site over a larger area and allows for a gradual rather than abrupt change in rigidity (13). The stress at any one point is further reduced by a vast number of individual fascicles that make up the cranial cruciate ligament. These fascicles spread out over a large area of bone to diffuse tension over a larger area.

1.4 Function of cranial cruciate ligament

The composition of the cranial cruciate ligament, its spatial orientation, and its anatomy are adapted to its function as a stabilizer of the stifle joint (3). The cranial cruciate ligament "is a necessary structure to the stability of the knee joint" (14). The cranial cruciate ligament, as well as the other ligaments of the stifle, controls the motion of the joint and restricts excessive movements (3, 15). This ligament is the principal stabilizer (16) of the joint and having three main constraining roles: (1) prevention of cranial movement of the tibia on the femur (cranial drawer effect), (2) prevention of joint hyperextension, and (3) restriction of the medial rotation of the tibia on the femur (11, 13, 17, 18).

In 1941, Brantigen and Voshell identified two parts of the cranial cruciate ligament which operate independently during extension and flexion (19, 20). The largest part of the ligament is loose in flexion and tight in extension (19). This segment of the cranial cruciate ligament is the caudolateral part (CLP). The remaining portion of the ligament, the craniomedial band (CMB), runs from the craniodorsal portion of the femoral attachment to the craniomedial portion of the tibial attachment, and is taut in both extension and flexion (19).

1.5 Kinematics of normal stifle joint

The constraints placed on the stifle by the cranial cruciate ligament and other ligaments of the joint combined with the anatomical position and shape of other stifle structures, produce a distinctive movement between the femur and tibia as the joint is flexed or extended.

This movement can best be described as a mixture of sliding and rolling movements. Pure sliding occurs when new points on the femoral articular surface continually come into contact with the same point on the tibial surface. Rolling occurs when new points on both articular surfaces continually come into contact with each other in points equidistant from each other (Figure 2). An initial 20-30° of flexion in the stifle is characterized by a combination of sliding and rolling movements, which are followed by a pure sliding movement (21). A mixture of rolling and sliding occurs if the points are not equidistant (21).

1.6 Causes of cranial cruciate ligament damage

When any excessive force is placed upon the stifle, particularly upon the cranial cruciate ligament, the ligament may tear. This allows abnormal movement in the injured stifle. The most common cause of cranial cruciate ligament lesions

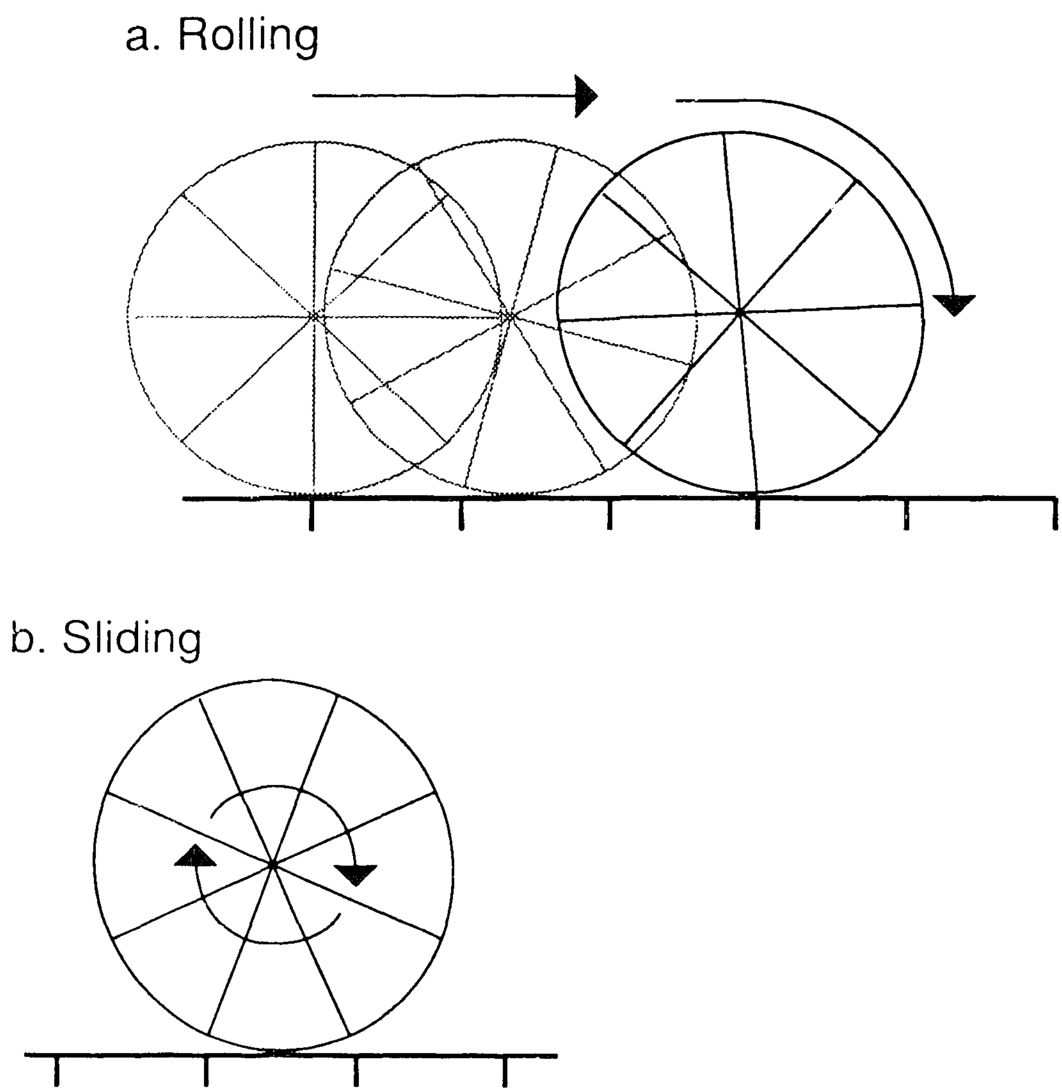


Figure 2

Schematic representation of the: a) rolling and b) sliding movement occurring between the articulating bones of a synovial joint.

is an abrupt axial rotation of the stifle when the joint is flexed 20-50°. Medial rotation of the tibia on the femur is limited by the twisting within each cruciate and of the cruciates around one another. If the stifle undergoes excessive medial rotation the highly twisted cranial cruciate ligament will rub against the rotating femoral condyle making the ligament susceptible to injury. A sudden turn on the weight-bearing rear limb subjects the animal to this type of injury. In mature animals, the injury may be a tear at the ligament's midpoint. In younger animals a detachment from the ligament's attachment site, an avulsion, usually occurs. Since the cranial cruciate ligament is the primary constraining structure for the prevention of hyperextension, it will be the first structure to be subject to trauma when the joint is hyperextended (13).

The majority of cranial cruciate ligament lesions are not due to acute trauma (13). They are the product of chronic degenerative alterations within the ultrastructure of the ligament (13, 22). As the internal derangement of the stifle joint evolves, the ultrastructure of the cranial cruciate ligament becomes altered due to recurrent small stresses placed on the joint. Hyalinization of the collagen fibres occurs, resulting in a decrease in the tensile strength of the ligament. The progressive reduction in the tensile strength makes the ligament more prone to injury from smaller stresses. There has been a correlation identified between this change in ligamentous ultrastructure and aging, which may be why the bulk of the cruciate ligament injuries are found in dogs five years of age and older (13, 22).

Patellar luxation is a common cause of chronic pathological changes in the cranial cruciate ligament. In patellar luxation, the cranial cruciate ligament must absorb additional stresses which are normally being borne by the quadriceps and the patellar ligament (13).

1.7 Kinematics of CCL ruptured stifle joint

If the cranial cruciate ligament is ruptured, the stability of the joint is altered and the relative movement of the stifle structures is changed. In a stifle with an acute cruciate tear, the joint is usually unable to fully extend or flex (23). Cruciate tear causes abnormal motion, possibly between bone surfaces, and may produce compression between the articulating surfaces. This will cause wear of the adjacent surfaces (menisci and articular cartilage) resulting in degenerative joint disease (23). Also, an acute cruciate tear usually results in the loss of a normal "screw-home" mechanism (23, 24). The screw-home movement involves the medial rotation of the femur in the final degrees of extension producing a locking mechanism. This medial rotation of the femur is due to the larger size of the medial femoral condyle and serves to stabilize the joint in the final degrees of extension.

1.8 Instantaneous centre of rotation

The relative movement of the articular surfaces of the joint can be evaluated at any degree of flexion or extension through kinematic studies. One method of describing the mechanical movement of planar joints is to use the instantaneous centres of rotation (ICR).

At any one instant in time, as one rigid body rotates about another in a single plane, there is a point that has no movement (zero velocity). This is the instantaneous centre of rotation or centrode (23). The stifle is not planar throughout its entire range of extension, but it is close enough to be considered planar (21, 24, 25). In the normal stifle joint, the ICR follows a characteristic pathway on the condyle of the femur during flexion (23). An irregular kinematic movement can be detected by the abnormal displacement of the ICR (23).

Besides being useful in identifying an abnormal movement in the injured joint, the instantaneous centre of rotation can also be used to determine the instantaneous direction of movement of every possible point on the moving bone. Therefore, the direction of velocity at the point of contact of the articulating surfaces can be determined (23). This is very important in the evaluation of the effectiveness of a method of joint repair or prosthetic installation. In both repair procedures and prosthesis the least amount of resistance, or minimal friction, is desired. Minimal friction occurs when the direction of velocity at the point of contact of the articular surfaces is tangent to the contact surface. This condition exists when the instantaneous centre of rotation lies on a line perpendicular to the articular surface at the point of contact (17, 23) (Figure 3).

Originally the ICR was located using the Rouleaux method (23). The Rouleaux method makes use of marker points chosen on the moving bone. The joint is flexed to a number of different positions and the location of each marker point is identified at each site. The vector displacements between consecutive marker point position are drawn. These displacements are perpendicularly bisected and the point of intersection of these perpendicular bisectors identifies the instantaneous centre of rotation for that displacement (Figure 4).

1.9 Inaccuracies in ICR methods

After the development of the Rouleaux method, various sources of error were identified (26, 27, 28, 29, 30). These sources include both experimental design and lack of accuracy when taking measurements.

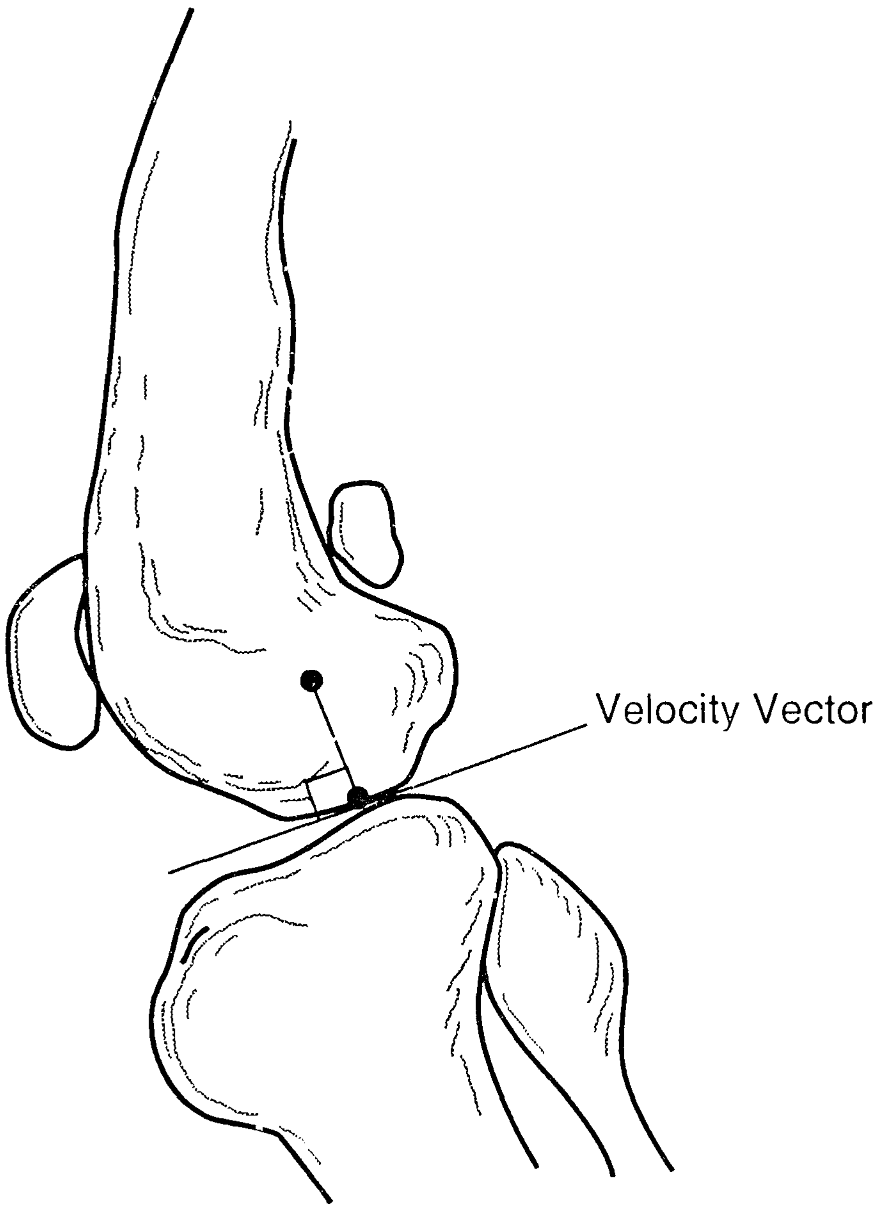


Figure 3

The least amount of friction between articulating surfaces is found when the velocity direction at the point of contact is tangential to the articular surface.

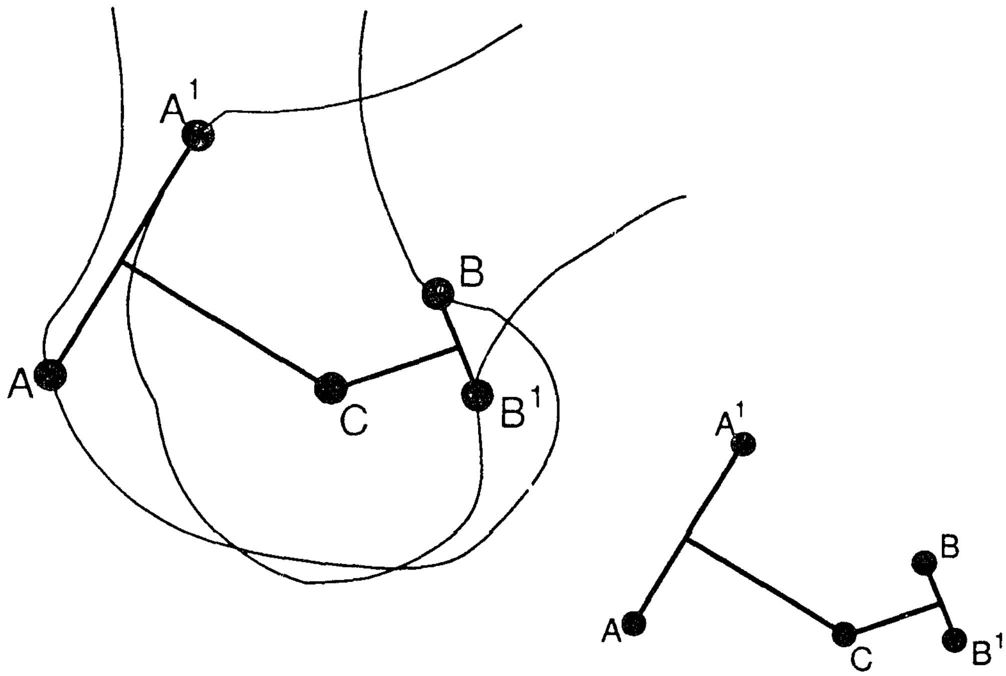


Figure 4

The identification of the instantaneous centre of rotation by the Rouleaux method. During flexion, marker points A and B were displaced to A^1 and B^1, respectively. Vectors were drawn between A and A^1, and B and B^1. These two vectors are perpendicularly bisected and the intersection of these perpendicular bisectors is the instantaneous centre of rotation (point C).

Panjabi (26) and Panjabi et al. (30) discussed areas of suboptimal experimental design which produced errors in locating the instantaneous centre of rotation. Means of reducing these errors were described. Factors which affected the accuracy in locating the instantaneous centre of rotation included the angle of rotation, the angle of the marker points, and the distance between the ICR and the marker points.

Increasing the angle of rotation decreased the location error of the instantaneous centre of rotation. They also stated a large increase in the location error of the instantaneous centre of rotation occurred when the angle of rotation is less than 5°. The location of the marker points also significantly affected the accuracy of determining the location of the instantaneous centre of rotation. The precision of the placement of the instantaneous centre of rotation was optimal when the angle between lines drawn from marker points to instantaneous centres of rotation was 90° (Figure 5).

The accuracy of the instantaneous centre of rotation location increased as the distance between the estimated instantaneous centre of rotation and the marker points, increased. However, as long as the distance was greater than 20mm, the effect was not important.

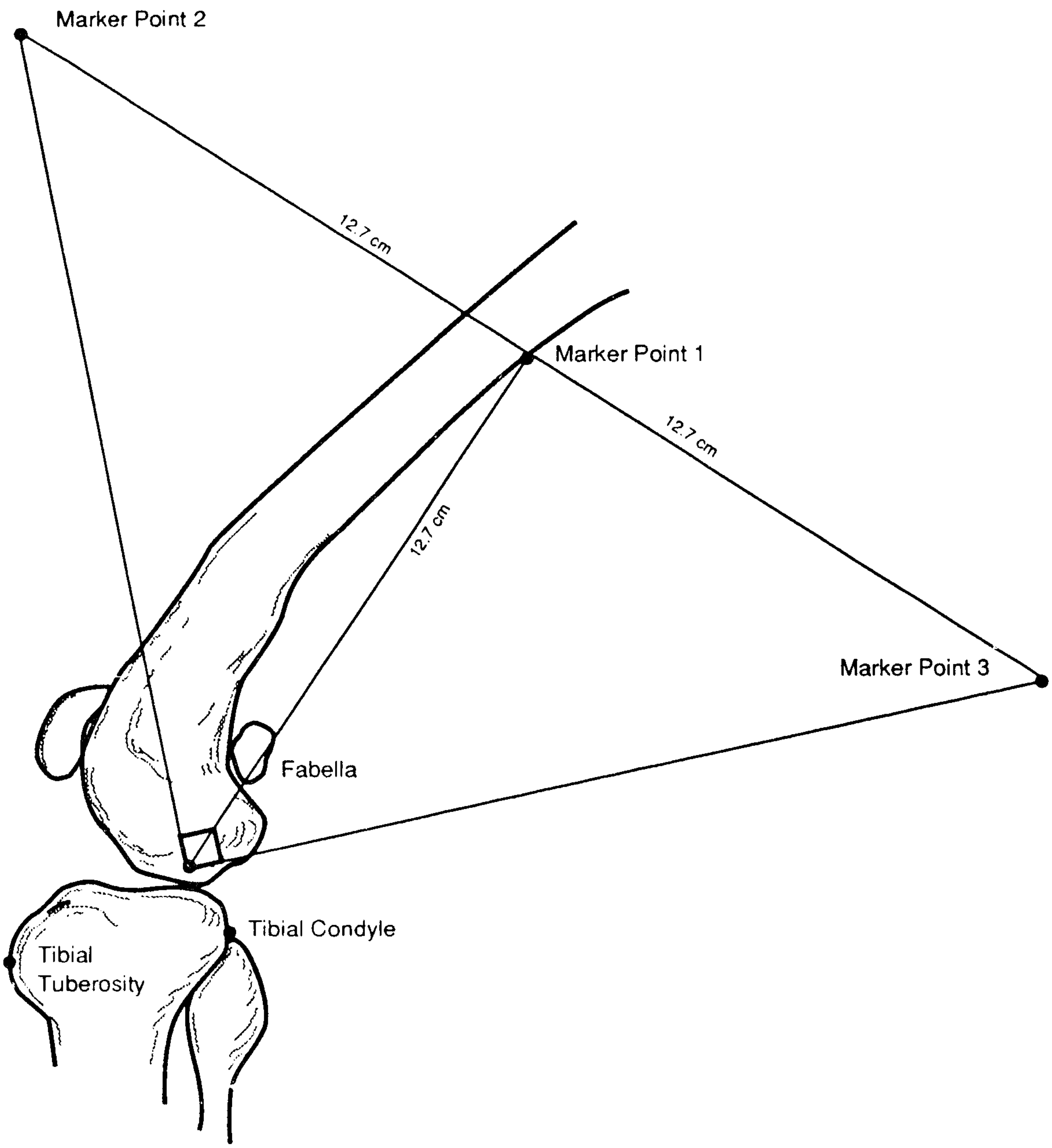


Figure 5

Depiction of an optimal marker point angle of 90°.

Panjabi also discussed the effects of measurement technique on the results. Small inaccuracies in the measurement of the marker point coordinates result in greatly magnified errors in the location of the instantaneous centre of rotation. The location error of the instantaneous centre of rotation increases and is greater than the measurement error of the marker point coordinates. Dimnet (29) reported on the maximum inaccuracy of locating an anatomical point and found that it always exceeds 0.8mm. Dimnet verified that by using angles and lines the accuracy of pinpointing specific positions is increased.

Soudan et al. (1978) (28) reported that the precision in locating the instantaneous centre of rotation is reduced if the joint movement is not kept parallel to the plane of the x-ray film. If the joint motion is not parallel to the film, the image produced is geometrically distorted (31).

1.10 Modified Rouleaux method

The modified Rouleaux method used in this study used curves drawn through each series of marker points. These curves smoothed the locations of the marker points, creating a pathway that more accurately shows the location of the marker points than the vectors used in the Rouleaux method. The curves were then perpendicularly bisected and the intersection of these perpendicular bisectors were then used to determine the instantaneous centre of rotation. The validity of this modified Rouleaux method was confirmed by Ireland et al. (32).

If no craniocaudal force is exerted on the leg with cranial cruciate ligament rupture, the instantaneous centre of rotation will not be altered (17). The ligaments of the stifle are taut during stifle motion. To mimic this condition the study was done with the cranial cruciate ligament in tension (3).

1.11 Surgical methods of CCL repair

There are a number of surgical procedures used in the repair of the cranial cruciate ligament. These can be categorized into two types: intra-articular and extra-articular. Intra-articular methods involve the use of an autograft or synthetic graft to replace the damaged cruciate; extra-articular methods stabilize the joint by modifying extra-articular structures.

Extra-articular techniques are generally successful in cats and dogs weighing less than 15 kg. One method, lateral retinacular imbrication, has been used very effectively in smaller animals (13). This technique involves the use of a heavy nonabsorbable suture positioned on the lateral aspect of the stifle so as to eliminate all drawer motion when tightened. In a modification of this technique by Flo (4), the medial aspect of the stifle is imbricated as well.

The purpose of the intra-articular methods is to replace the cranial cruciate ligament with a substitute that has the same spatial orientation and anatomical positioning as the original ligament. Intra-articular ligament replacement techniques utilizing synthetic graft materials have shown only limited success. These materials have included dacron (33, 34), carbon fibres (35), and polypropylene (36). In most cases, the synthetic graft is used as a scaffold for the support and proliferation of connective tissue which forms a new ligament. Dacron has been only partially successful in developing a new ligament. It has the ability to support connective tissue growth, but the orientation of the tissue is unorganized. It has been theorized this random arrangement of tissue in the neoligament is due to the lack of mechanical stimuli. The initial rigidity of the graft prevents the exposure of the mechanical forces on the graft necessary to stimulate the organization of the graft ultrastructure (36).

Better success has been achieved with autograft and allograft cranial cruciate replacements. Autografts have utilized semimembranosus tendon (37), semitendonosus tendon (38), fascia lata (39), and patellar tendon (40). Freeze-dried ligamentous allografts have demonstrated much potential as cruciate substitutes, being both functional and biocompatible as a replacement (41, 42).

The surgical technique evaluated in this study was a modification of the intra-articular procedure called the over-the-top technique. This technique involves the isolation of the medial third of the patellar tendon, patella, and patellar ligament. The distal end of the graft is left attached to the tibial tuberosity (Figure 6). The free end of the graft was passed through the intercondylar notch and over the lateral femoral condyle. The graft was tightened to stabilize the joint and attached to the soft tissues of the lateral femoral condyle (8, 13, 43). At this point, the technique was modified by the addition of medial and lateral imbrication sutures of non-absorbable suture. The imbrication sutures were to serve as an internal splint to take the majority of the stress off the graft for the first few weeks.

No one repair procedure is best for all sizes and breeds of dogs (43). The over-the-top technique seems to work best and produce long-term stability in dogs weighing 15 kg or more (43). The clinical success rate of the over-the-top technique in larger dogs is good (8). An advantage of this technique compared with other procedures is that it provides a consistent anatomical replacement of the cranial cruciate ligament in the larger dogs. Also, with the over-the-top technique there is no wearing of the graft on the edge of the drill hole needed for many substitution methods (8). In order to predict success with any cruciate replacement or repair technique, a thorough evaluation of other stifle structures

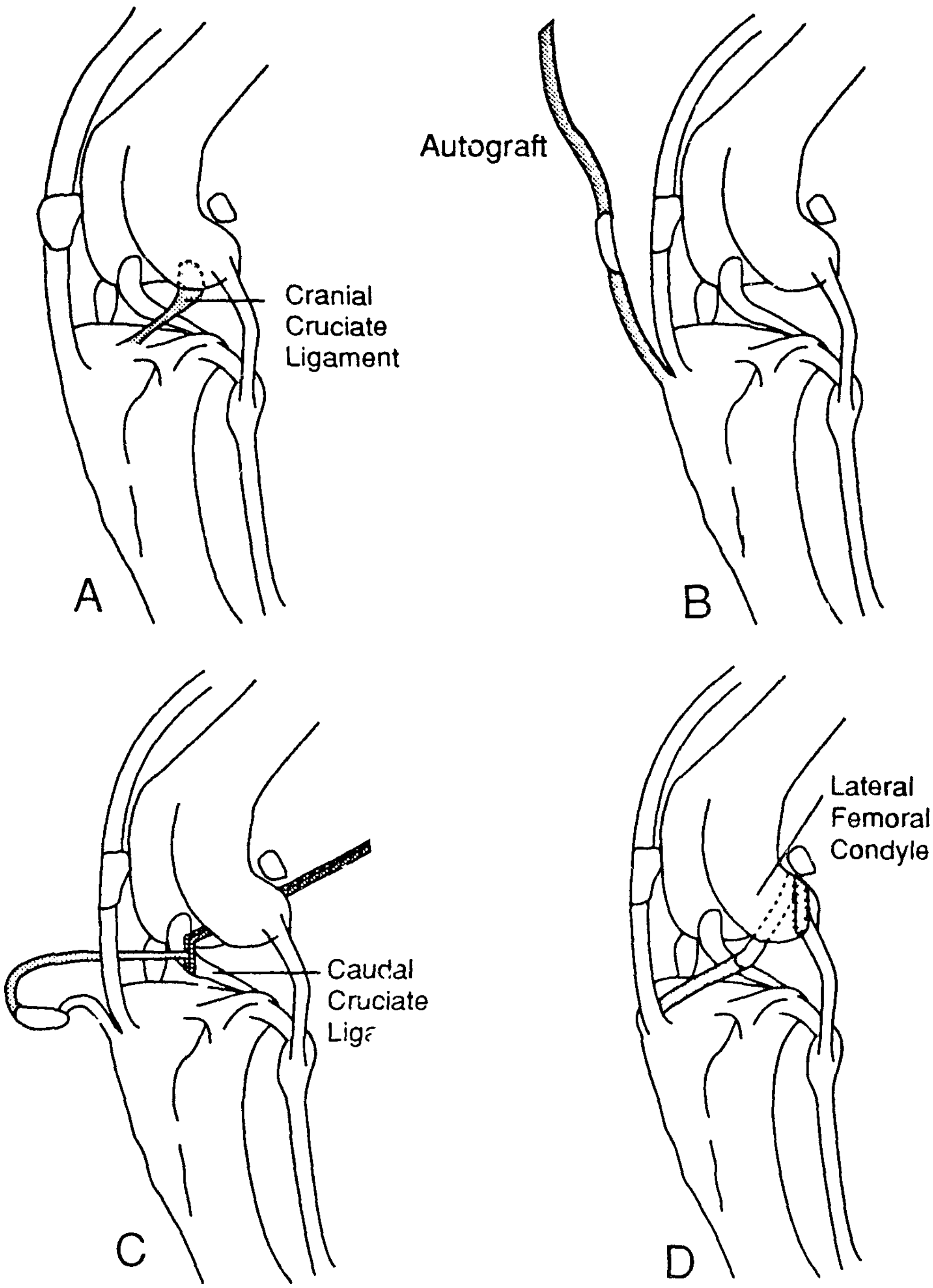


Figure 6

Craniolateral view of the left stifle showing: (A) the normal position of the cranial cruciate ligament, (B) the isolated graft used to replace the cranial cruciate ligament in the over-the-top technique, (C) the tips of the hemostats in the intercondylar notch, lateral to the caudal cruciate ligament, holding the free end of the autograft, and (D) the orientation of the graft in the joint with its attachment to the lateral femoral condyle.

(patella, caudal cruciate ligament, collateral ligaments, menisci) must be performed. In many cranial cruciate rupture cases for instance, meniscal lesions are present (44).

2. INTRODUCTION

In 1952, Paatasma identified the cranial cruciate ligament as the most commonly injured ligament in the stifle joint of dogs (13). The cranial cruciate ligament is primarily responsible for craniocaudal stability of the stifle, preventing the cranial displacement of the tibia relative to the femur (3, 19, 45). Since 1952, a large number of procedures and materials have been utilized to repair the cranial cruciate ligament (33, 36, 42, 43, 44, 47, 48, 49, 50) including a variety of intra-articular and extra-articular techniques.

Intra-articular methods involve the replacement of the cranial cruciate ligament with an autogenous, allogenous, or synthetic graft. One intra-articular method is the over-the-top technique (8). The extra-articular procedures tighten extra-articular structures in order to stabilize the joint. Of these two types, the intra-articular procedures have been reported to be most effective in producing normal postoperative stifle movement in dogs weighing over 30 Kg (17, 47).

To date, methods of cranial cruciate ligament repair have been evaluated using a number of subjective measurements, including the degree of postoperative lameness, gait, cranial drawer sign, and satisfaction of the client (8, 22, 46, 47, 50). An accurate objective method of evaluation would aid to determine the effectiveness of the different surgical repair methods. The evaluation has to answer two questions: (1) Are the biomechanics of the cruciate torn stifle altered from that of normal stifle and (2) are the biomechanics restored to normal after the repair.

One objective method of evaluating joint biomechanics is the instantaneous centre of rotation in the plane. At any one moment in time, as one rigid body rotates about another, there is a point on the rotating body which has zero velocity or no movement. It is this point which is known as the instantaneous centre of rotation. In the case of the stifle joint, the rigid bodies are the tibia and femur. Because the instantaneous centre is not moving at a particular given moment, it can be used as a reference point to determine how one bone moves in relation to another. If the instantaneous centre at every possible instant is known, then all aspects of movement of the two bones relative to each other can be described.

Originally the locations of the instantaneous centre were identified by the use of the Rouleaux method (23). The Rouleaux method makes use of marker points chosen on the moving bone. The joint is flexed to a number of different locations and the position of each marker point is identified at each site. The vector displacements between consecutive marker point positions are drawn. These displacements are perpendicularly bisected and the point of intersection of these perpendicular bisectors identifies the instantaneous centre of rotation for that displacement (23).

After the formulation of the Rouleaux method, many sources of error in locating the instantaneous centre of rotation by this method were identified (26, 27, 28, 29, 30). Panjabi (26) reported on the effects of the angle of rotation, the angle of the marker points, the distance between the marker point and the estimated instantaneous centre of rotation, and the inaccuracies in the measurement of the marker point coordinates.

In order to optimize the accuracy in locating the instantaneous centre of rotation, the angle of rotation should be large and the angle of marker points should be 90° (26, 27). Better precision in locating the instantaneous centre of rotation is found by increasing the distance between the estimated instantaneous centre of rotation and the marker points. Panjabi also stated that small inaccuracies in the measurement of the marker point coordinates result in greatly magnified errors in the location of the instantaneous centre of rotation (26).

The inherent inaccuracy in locating an anatomical point was quantified by Dimnet (29) and found to always exceed 0.8mm. Dimnet verified by using angles and lines, the accuracy of pinpointing specific positions is increased. In 1978, Soudan et al. (28) maintained that if the joint is not kept parallel to the plane of the x-ray film, the precision in locating the instantaneous centre of rotation would be reduced because of geometric distortion.

The technique used in this study was a modification of the Rouleaux method and minimized the possible errors in order to optimize the results. In place of vectors, curves were used to smooth the marker point positions, producing a pathway which more accurately shows the location of the marker points. The validity of this method was established by Ireland et al. (32). The results of this study were thus optimised by taking into consideration the parameters producing error which had been identified in the literature, and designing the experimental procedure so the error was as small as possible.

Because the instantaneous centre describes joint motion, its position indicates the normal movement of the joint. Measurement of the instantaneous centre can be used to determine if surgery restores normal stifle movement following injury. There is no significant difference in the instantaneous centre position between the normal hind legs, therefore the stifle movement of an injured leg can be compared to the contralateral uninjured leg as a control (32).

The purpose of this paper is to present a method for objectively evaluating a modified over-the-top method of cruciate repair (8). This method involved the localization of the instantaneous centre of rotation at different degrees of flexion. It was hypothesized that the stifle with the ruptured cruciate would be biomechanically abnormal because in the absence of the cranial cruciate ligament there would be a cranial movement of the tibia relative to the femur. This would then result in an overall caudal displacement of the instantaneous centre of rotation with respect to the tibia. It was also anticipated the stifle would be biomechanically restored to normal following surgery, since the neoligament in the over-the-top technique nearly duplicated the pathway of the original ligament.

3. MATERIALS AND METHODS

Dogs presented for hind limb lameness were evaluated for a cranial cruciate ligament rupture. Those diagnosed with a unilateral cranial cruciate ligament rupture were used in the study. The normal and injured stifles were radiographed with an image intensifier (Machlett) while being flexed through their full range. The injured cranial cruciate ligament was then surgically replaced with an intra-articular autograft (over-the-top procedure). Six weeks after surgery the repaired joint was re-evaluated radiographically.

The image produced from each radiographic session was recorded on VHS video cassette (BASF, T120, Chrome super high grade) and later viewed on a television screen (Sony, Trinatron). Pictures were taken at different angles of flexion. The x-axis and y-axis coordinates of anatomical points on each photograph were identified by a digitizer (Scriptel Digitizer). These coordinates were entered into a user written computer program, which calculated the positions of instantaneous centres of rotation. Finally, multivariate analyses of variance were performed on the instantaneous centres of rotation coordinates to determine if there were significant differences between the control (normal) limb, the injured limb, and the repaired limb.

Seven dogs of differing breeds, aged between 2 and 11, years, were used to conduct this study. These dogs, four females and three males, had an average weight of 37.7 Kg (Table 1). Each dog was clinically diagnosed as having a cranial cruciate ligament rupture by direct observation of an acute hind limb lameness and by elicitation of a positive cranial drawer sign symptomatic of stifle instability. The drawer sign was also used by the surgeon to evaluate the subjective severity of laxity in the damaged joint, and to rate the severity of the rupture numerically from 0 to 4, (normal (0), to mild (1), moderate (2), severe (3), and very severe (4)) (Table 2).

3.1 Radiographic procedure

After observation and evaluation of the injured stifle, each dog was anaesthetized for fluoroscopic examination using an image intensifier of both

TABLE 1 Breed, age, sex, and weight of each dog used in the study

Dog	Breed	Age (years)	Sex	Weight Kg
1	Labrador Retriever	4.5	F	33.0
2	Golden Retriever	10.5	M	29.0
3	Newfoundland	4.0	F	36.6
4	Doberman Pinscher	5.0	M	45.0
5	Malamute	9.0	F	37.6
6	Samoyed	6.5	M	50.8
7	Labrador Retriever	2.0	F	32.0

TABLE 2 Severity of laxity of the injured stifle, subjectively evaluated by the surgeon and time lapse between the first symptoms of lameness and surgery. The severity of stifle laxity was rated numerically from 0 to 4, normal (0), mild (1), moderate (2), severe (3), and very severe (4).

Dog	Severity of Laxity	Injured Stifle	Time Lapse Between Observable Lameness and Surgery
1	2	Right	8 months
2	1	Left	1 month
3	3	Right	24 months
4	3	Left	2.5 weeks
5	2	Left	2 weeks
6	3	Left	1 month
7	3	Left	unknown

damaged and normal stifles. During each radiographic session the dog was placed in lateral recumbency on the x-ray table (Picker, Universix 20). The limb to be radiographed was closest to the table and parallel to the lens of an x-ray image intensifier mounted under the table. A collimator was used to position the central x-ray beam so that the tibial tuberosity, tibial condyle, and as much of the femur as possible were radiographed. The opposite limb was retracted out of the image intensifier field so that areas of interest were not obscured.

During radiographic sessions, tension was placed on the stifle by a wide leather strap to mimic the cranial tibial thrust that would be placed on the joint during active movement (51). The strap was placed around the proximal caudal aspect of the tibia just below the tibial tuberosity and extended cranial to the tibia approximately 30 centimetres. A force of 35 newtons was exerted on the tibia in a cranial direction by pulling on a small force scale placed at the end of the strap (Figure 7). The force was kept perpendicular to the axis of the tibia at all times. The femur was maintained in a stationary position by a wooden block placed on the cranial aspect of the femur, allowing the operator's hand to stay out of the x-ray beam.

The femur was held parallel to the table to prevent axial rotation of the femur and geometric distortion while the joint was being flexed. Distortion

Figure 7

Cranial force of 35.58 newtons placed on the proximal aspect of the tibia to mimic the cranial tibial thrust found in normal stifle movement.

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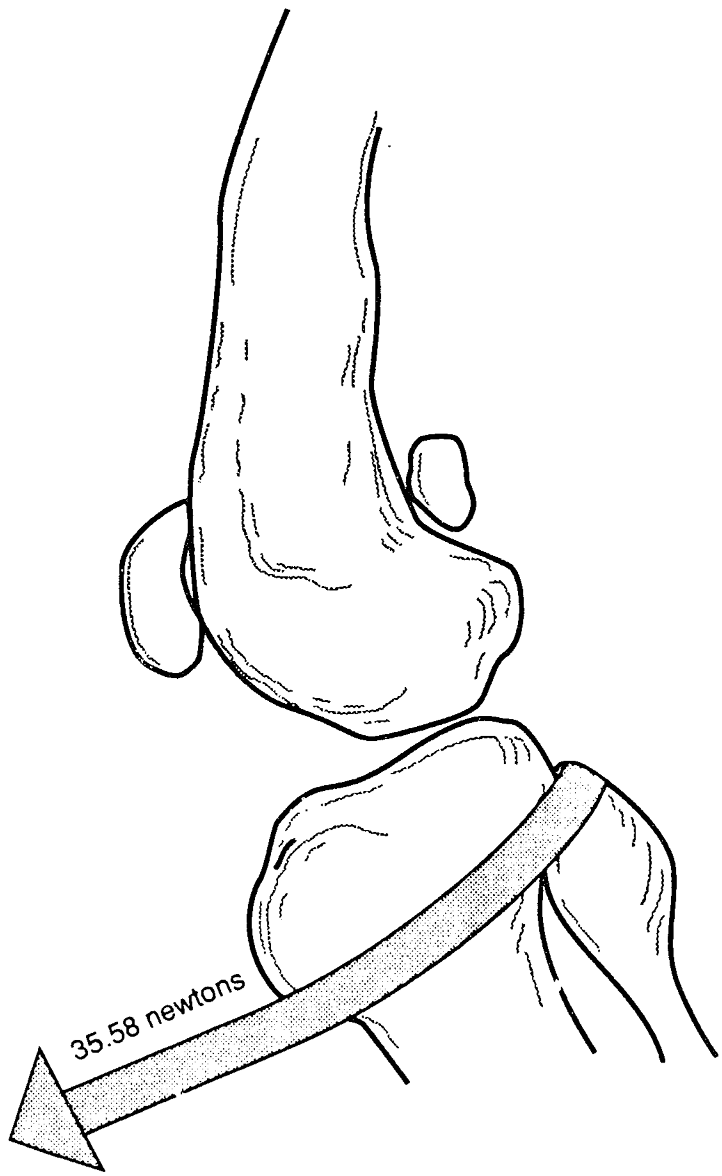


Figure 7

Cranial force of 35.58 newtons placed on the proximal aspect of the tibia to mimic the cranial tibial thrust found in normal stifle movement.

was further reduced by keeping the central x-ray beam perpendicular to the plane of the joint movement (31). The stifle angle can be considered the vertex of an angle between the caudal tibia and caudal femur (Figure 8). As the stifle flexes this angle becomes smaller, to a minimum of approximately 40°. The angle increases to about 150° when the stifle is fully extended.

The tibia was moved slowly from full extension to full flexion, while the 35 newton force was kept perpendicular to the long axis of the tibia. During exposure, the image intensifier created an image on a closed circuit television screen. This allowed the operator to ensure that the anatomical points of interest stayed within the image intensifier's field during the tibial flexion. Simultaneously, the television image was recorded by a video cassette recorder (JVC, VHS, High Quality, Hi-Fi) onto a VHS cassette .

3.2 Surgical method of repair

After radiography, the injured stifle joint was repaired. The surgical procedure used to replace the cranial cruciate ligament rupture was an intra-articular technique called the over-the-top procedure. This technique uses the medial third of the patellar ligament-patella-patellar tendon as an autograft. The autograft complex was left attached distally to the tibial tuberosity. The adjoining

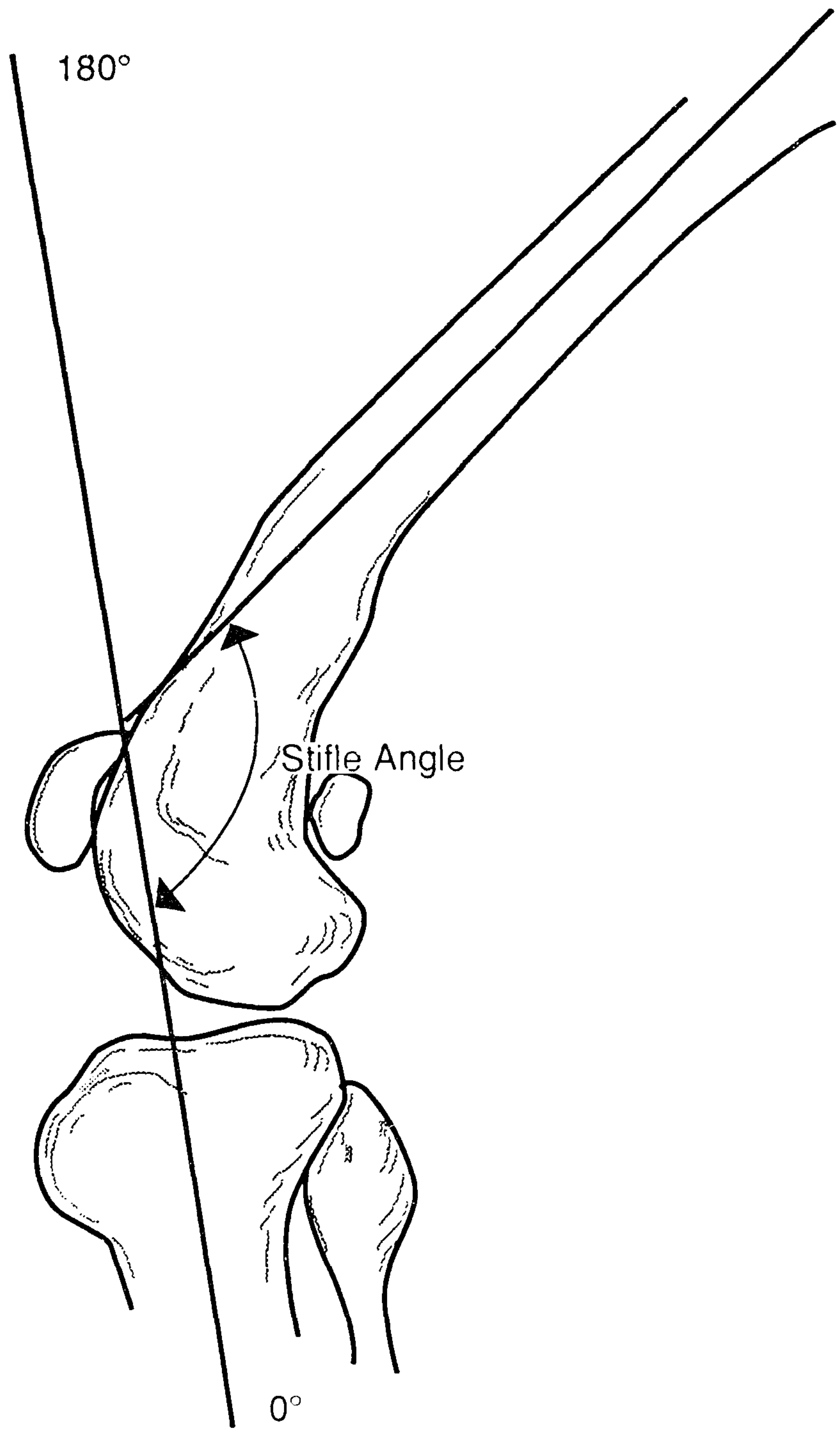


Figure 8

Illustration of the method used in the determination of stifle angles.

fat pad was left intact. After the graft had been isolated, the joir was maximally flexed and remnants of the ruptured ligament and any lesic removed. The tips of curved haemostats were then carefully placed in the intercondylar notch by pushing them over the lateral femoral condyle. During this placement, care was taken not to disturb articular structures. The graft was grasped by the haemostats and pulled through the intercondylar notch and over the top of the lateral femoral condyle. Enough traction was placed on the graft to remove the abnormal cranial drawer motion. The graft was then sutured to the soft tissues around the lateral femoral condyle (8). Following the routine closure of the joint capsule, the joint was laterally and medially imbricated (22) with #2 nylon to reduce the force placed on the graft during the initial postoperative healing phase.

Six weeks postoperatively, the dogs were sedated and the repaired limb was radiographed using the same procedure employed preoperative.

3.3 Photography and digitization

Using the video recorder and a television screen , the recorded radiographic images were displayed. This image on the screen became distorted horizontally, forming an ellipse. This distortion made it necessary to adjust all points digitized from the photograph. The stifle image was paused every 10° during the play-back, beginning with a stifle angle of 150° and ending at 40°, so that it could be photographed with a 35 mm camera (Nikon) placed 30 cm away from the viewing screen. The film (Kodak Tri-X 400 black/white) was developed using Kodak D-76 developer. Prints were made on multigrade paper at high contrast using an enlarger (Focomat V35 Autofocus) equipped with a 40mm lens. The print was then automatically processed (Ilford Ilospeed 2240) with Ilford Ilospeed 2000 developer and fixer.

Photographs were placed on a high resolution (.025mm) digitizer tablet which functioned as an electronic drawing board to enter position information from the photograph. The lower edge of the photograph was digitized to assist in the correction of the horizontal distortion caused by the television screen.

On each individual photograph the tibial tuberosity was first located and digitized. The most caudal point of the tibial condyle was then digitized followed by digitization of the lateral fabella. The location of a first marker point was determined by digitizing successive proximal points on the caudal border of the femur until a point 12.7 centimetres from the fabella was identified. This marker point, designated Marker Point 1, along with the tibial tuberosity, tibial condyle, and fabella were each digitized five times on each photograph. The average locations of each of these anatomical points was determined by adding the values of the x and y coordinates separately for the five trials and dividing by five. The coordinates of the second and third marker points were found by drawing a line through the first marker point, perpendicular to the femorofabellar line and measuring a distance of 12.7 centimetres to the left (Marker Point 2) and to the right (Marker point 3) of the first marker point (Figure 9).

To correct for misplacement of the digitized points caused by the distortion, the ratio between the length of the minor axis and the length of the major axis of the elliptical image on the television screen had to be calculated. In order to use this ratio (correction constant), the elliptical image on the photograph was rotated, so that the major axis of the ellipse was parallel to the x-axis and the minor axis was parallel to the y-axis. The x-coordinate of each point digitized was first rotated to conform to this orientation and then was multiplied by the correction constant to correct for the distortion. Since there was no distortion along the y-axis, the y coordinate did not have to be adjusted.

3.4 Finding and plotting the ICR

The coordinates of Marker Points 1, 2, and 3 were used to locate the instantaneous centre for each series of four sequential photographs. Common X

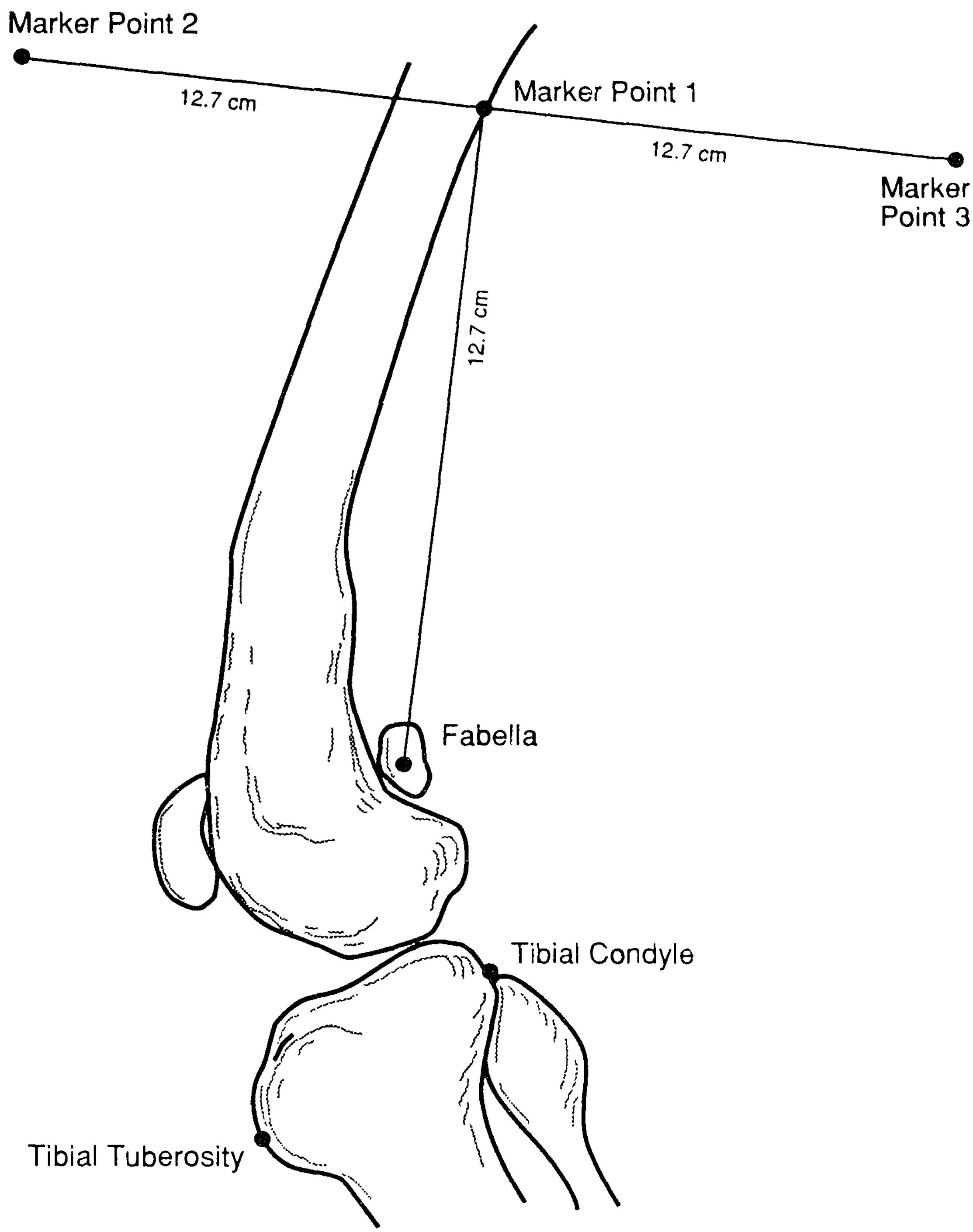
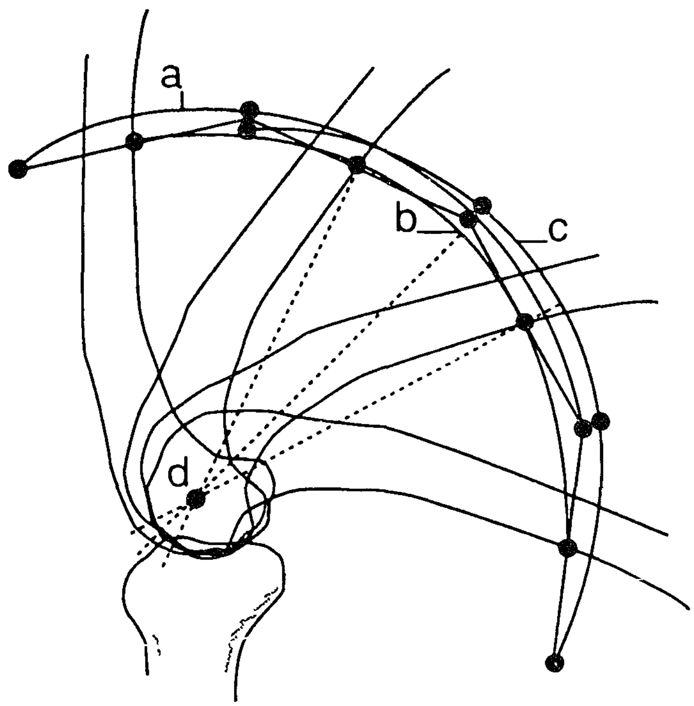


Figure 9

Locations of the reference points, (the tibial tuberosity and tibial condyle), and the marker points: (Marker point 1, marker point 2, and marker point 3), of the left stifle.

and Y axes were established for all four photographs by translating the tibial tuberosity to the origin and rotating the tibial condyle until it became situated on the X-axis of a coordinate system. This allowed for the examination of the relative movement of the three marker points in consecutive photographs.

A modification of the Rouleaux method was used to establish instantaneous centres of rotation from the marker points. A quadratic curve was fitted through each series of four consecutive positions of Marker Points 1, 2, and 3. This was done by beginning with the position of each Marker Point in the first photograph (stifle angle of 150°) and ending with positions of the marker points in the fourth photograph (stifle angle of 120°). These curves were then perpendicularly bisected. Next, curves were fitted through the marker points on photographs two through five. Again the curves were perpendicularly bisected. This procedure was repeated until all the positions of the Marker Points were fitted by quadratic curves in sets of four. Similar curves were fitted to Marker Point 2 positions and Marker Point 3 positions and bisected (Figure 10). The intersection of the perpendicular bisectors for the three curves created from each sequential series of four photographs was designated the instantaneous centre of rotation for that particular displacement (32). These instantaneous centres of rotation positions were then found and plotted using the tibial tuberosity to tibial condyle as a coordinate system.



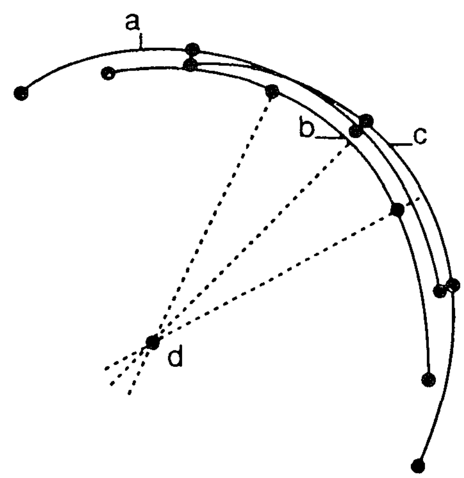


Figure 10

Identification of the instantaneous centre of rotation by a modified Rouleaux method that makes use of smooth fitting curves. Three quadratic curves (a,b,c) were fit through each series of marker point positions. The perpendicular to the tangent of the midpoint of each curve (dashed line) is drawn and the intersection of the three lines (d) is the instantaneous centre of rotation.

Experimental results in this study were optimized by taking into consideration the various parameters discussed above (Table 3). First, the angle of rotation was set at 40°. Second, the marker point positions were arranged so that the angle of these points was 90°. Third, the distance between the estimated instantaneous centre of rotation and the marker points was contrived so that Panjabi's lower limit of 20mm was exceeded. Fourth, the precision of the coordinates of the marker points was increased by using a high resolution digitizer (.025mm) and averaging the results of 5 coordinate measurements for each point measured. Fifth, extreme care was taken to position the joint so that the plane of movement was parallel to the x-ray film and that the central beam passed through the centre of the joint. This minimized any geometrical distortion of the bones (31).

3.5 Normalization and statistical analysis

The ICR values for each dog were normalized by dividing the ICR values by the distance between the tibial tuberosity and tibial condyle of that dog. The statistical analysis consisted of a three factor multivariate analysis of variance. The factors were the treatments (normal, injured, and repaired), the

TABLE 3. Methods Used to Reduce Experimental Error.

Experimental:	1) marker angle = 90°
	2) max. ICR-marker point distance (>2 cm)
	3) max. angle of rotation (>5°)
	4) cranial tibial force
	5) lines and points instead of anatomical landmarks
Radiographic	1) image intensifier to take radiographic image - more accurate angle measurements, therefore can compare the ICR at a particular angel more accurately.
	2) plane of joint rotation parallel to image intensifier - decreases geometric distortion.
	3) central x-ray beam through joint centre -decreases geometric distortion.
Measurement:	1) high resolution digitizer - eyes limiting the accuracy (0.8 mm)
	2) multiple measurement of marker and reference points and use average in calculations.

stifle angles (150° to 40°), and the dogs. The two outcome variables were the normalized x-axis and y-axis coordinates. Due to the presence of missing values the analysis was done using the GLM (general linear model) procedure in the Statistical Analysis System (SAS) statistical package (5) on the IBM at the University of New Brunswick. When significant mean squares were found, Scheffe's test was used to isolate the particular range and/or treatment contrasts that were significant (53).

4. RESULTS

4.1 Statistical analysis of data

A preliminary correlation coefficient showed a significant association ($t=7.51$, $Df=131$, $P<.001$) between the x and y coordinates of the instantaneous centre of rotation positions. Thus, a multivariate analyses was performed on the data. The analyses, according to Wilks' criterion (53), revealed at least one significant difference between the control, injured, and repaired stifles. To identify the source of significance univariate analyses were done on the x and y coordinates separately.

The univariate analyses on the x-coordinate showed a significant difference with treatments ($F=6.30$, $df=2$, $df=51$, $P< 0.004$). Scheffe's test identified the difference to be between the control and the injured stifles [mean= 2.65455 mm +/- 2.20751 mm (95% C.I.)]. The x-coordinate means of the instantaneous centre of rotation for the different treatments identified the difference as a caudal displacement (3.43mm) of the instantaneous centre of rotation in the injured stifle when compared to the mean instantaneous centre of rotation of the control stifle. There was no significant difference between the x-coordinate positions of the instantaneous centre of rotation in the repaired and normal stifles indicating that the repaired limb had near normal movement. The x-coordinate means of the instantaneous centre of rotation for the repaired limb showed a partial restoration, with only a 0.89 mm caudal displacement relative to the mean position of the instantaneous centre of rotation of the control limb (Figure 11).

The univariate analyses also identified a significant difference ($F=5.91$, $df=2$, $df=51$,$P< 0.005$) in the y-coordinates of the instantaneous centre of rotation positions amidst the treatments. Scheffe's test showed that this difference [mean= 3.6007 mm +/- 2.15392 mm (95% C.I.)] was between the control and the injured stifles. The mean location of the instantaneous centre of rotation, with respect to the y-coordinates. moved proximally by 3.94 mm in the injured stifle

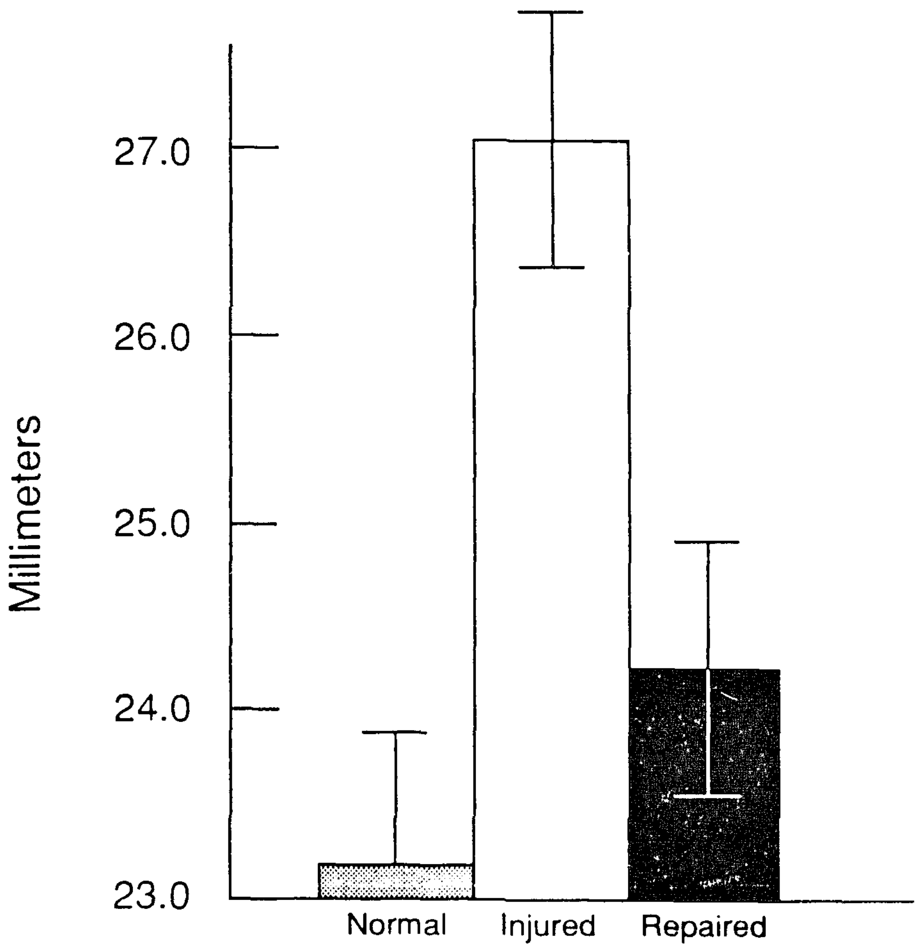


Figure 11

The mean (+/- standard deviation) x-coordinate position for the instantaneous center of rotation for the normal (N=42), injured (N=45), and repaired (N=47) stifles.

when compared to the mean instantaneous centre of rotation of the normal stifle (Figure 12). No significant difference between the y-coordinates of the repaired and normal stifle was found. In the repaired limb, the mean y-coordinate for the instantaneous centre of rotation was partially restored to a proximal displacement of 2.8 mm, relative to the mean instantaneous centre of rotation of the normal stifle. A significant range effect was identified by the multivariate analysis of variance, according to Wilks' criterion. This indicates that a significant difference exists between at least two of the angulations with respect to the instantaneous centre of rotation.

4.2 Graphical analysis of data

The treatment conditions were compared graphically at different ranges of motion. There was an initial caudal movement of the instantaneous centre of rotation in the injured stifle, whereas the control and repaired conditions show an initial cranial movement. Between stifle angles of 135° and 90° the injured limb has an instantaneous centre which was caudally displaced approximately 2.5 mm when compared to the normal limb (Figure 13). At a stifle angle of the 90°, pathways of the instantaneous centre of rotation for the three treatments intersect, and the instantaneous centre of rotation of the injured limb then moves cranial to the instantaneous centre of rotation of the normal stifle.

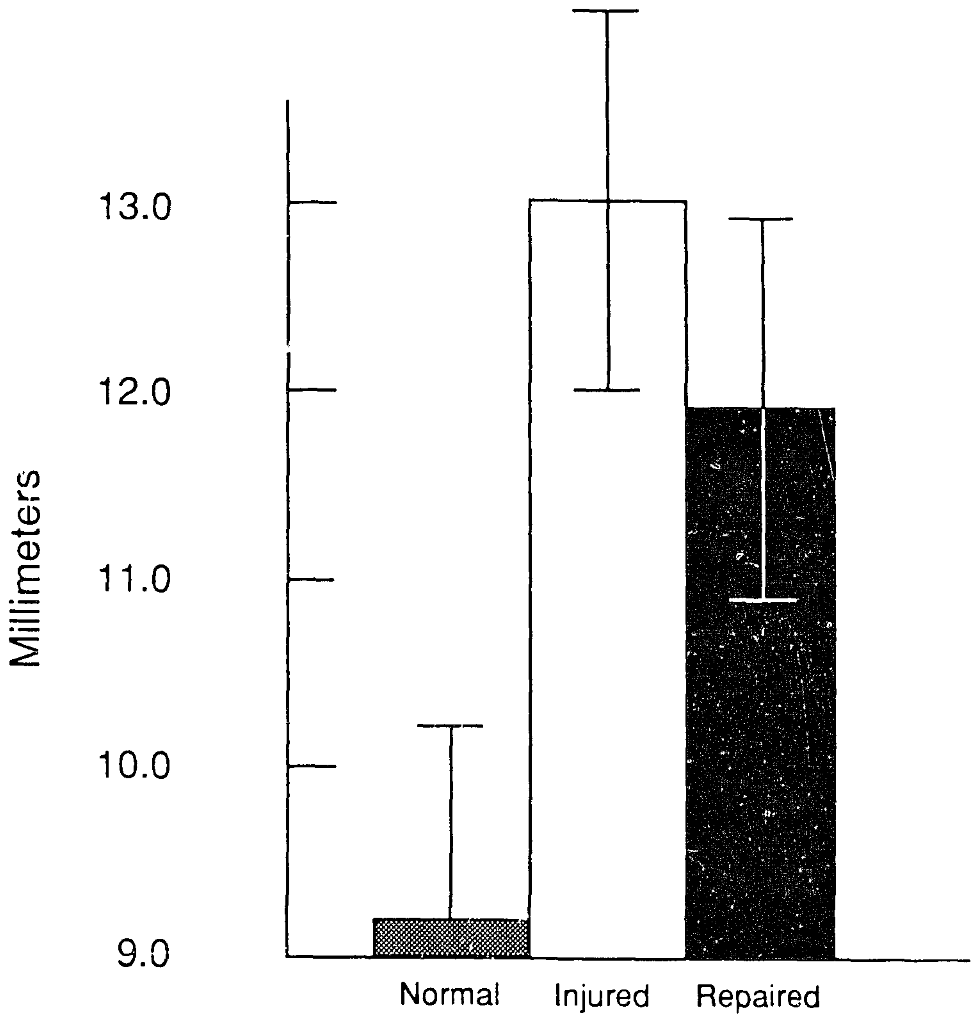


Figure 12

The mean (+/- standard deviation) y-coordinate position for the instantaneous center of rotation for the normal (N=42), injured (N=45), and repaired (N=47) stifles.

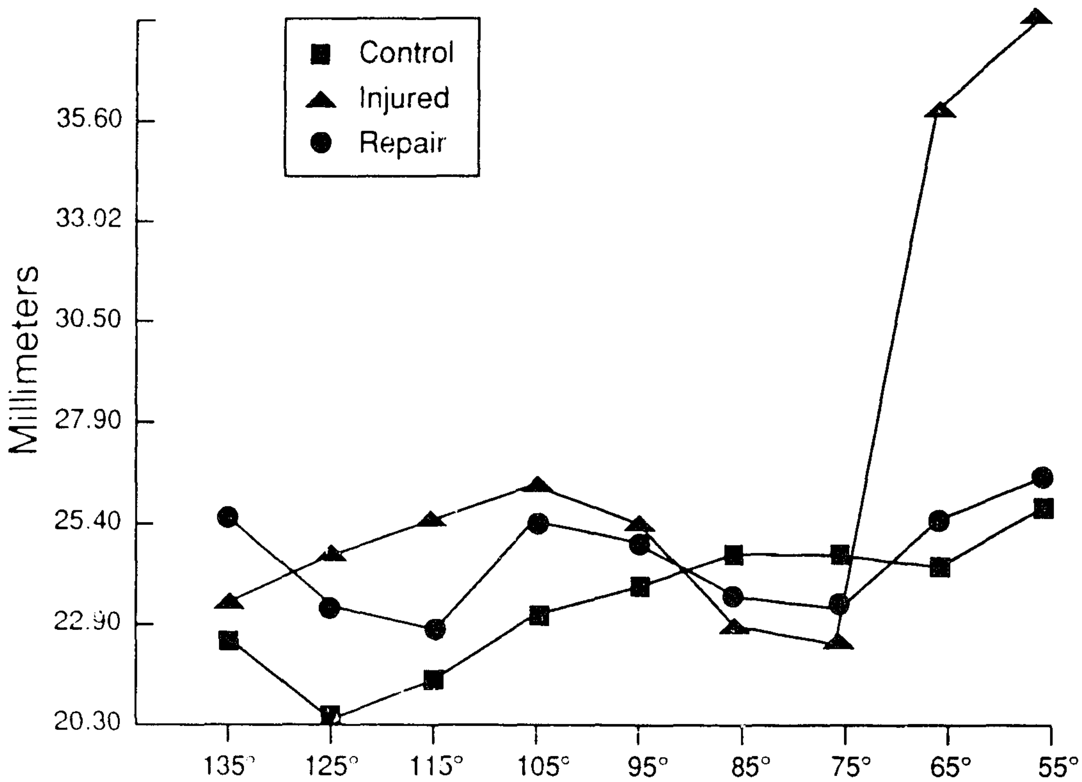


Figure 13

The mean x-coordinate position of the instantaneous center of joint rotation for the different angulations of the stifle joint.

The instantaneous centre of rotation of the injured stifle remains cranial to the instantaneous centre of rotation of the control limb until 105° of flexion.

Between stifle angles of 75⁰ and 55° of flexion there was a sharp caudal displacement of approximately 11 mm in the location of the instantaneous centre of rotation of the injured stifle relative to that of the normal stifle. Repair of the limb did not completely restore the normal pathway of the instantaneous centre. However, the trajectory did not differ appreciably from that of the normal limb (Figure 13). For all angulations, except for the initial few angles of flexion, the instantaneous centre of rotation pathway for the repaired stifle more closely matched that of the normal stifle than did the instantaneous centre of rotation pathway of the injured stifle

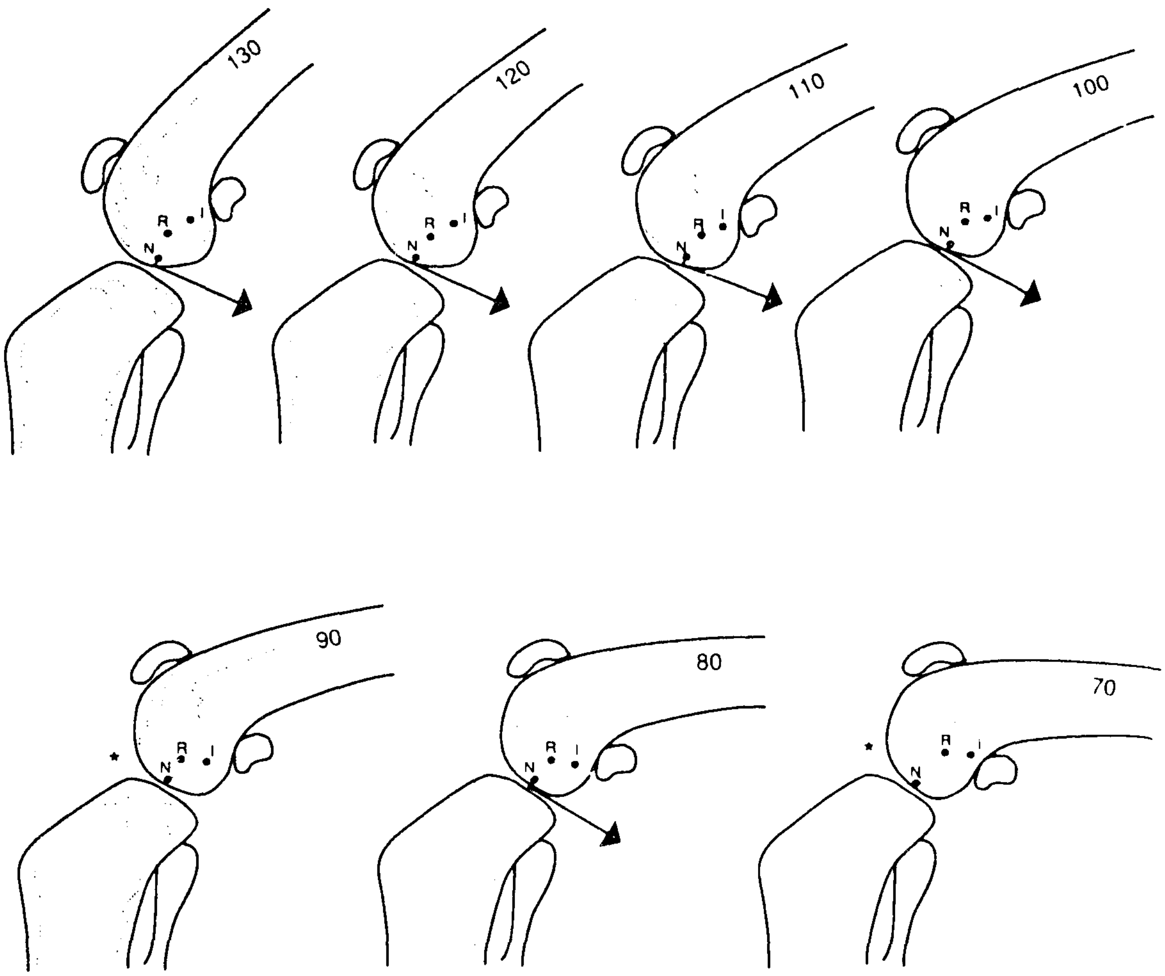
4.3 Positions of instantaneous centres on the femur

The instantaneous centre of rotation positions between stifle angles of 130° and 60° were on the normal, injured, and repaired femoral condyles. In the normal stifle, the positions of the instantaneous centre of rotation were found to be at or near the articular surface of the femoral condyle. In the cases where the instantaneous centres of rotation were not exactly on the articular surface, the instantaneous centres were on the perpendicular to tangent of the articular surface at the point of contact (Figure 14).

In the injured stifle there was a caudal and proximal displacement of the instantaneous centre of rotation from the contact surface at all angles of flexion. The positions of the instantaneous centre of rotation were not perpendicular to the tangent of the articular surface at the point of contact (Figure 15).

In the repaired stifle there is a partial restoration of the instantaneous centre of rotation positions to normal with less displacement from the articular surface than in the injured stifle. The instantaneous centre of rotation positions of the repaired stifle were perpendicular or approximately perpendicular to the tangent of the articular surface at the point of contact between stifle angles of 130° and 80° but not between 70° and 60° (Figure 16).

In summary, our results indicate that in the damaged stifle the instantaneous centre of rotation was significantly more caudal and proximal than the instantaneous centre of rotation of the normal stifle for the majority of angulations. This difference was especially pronounced in limbs flexed 75° to 55°. The repaired limb showed a partial re-establishment of the instantaneous centre of rotation to normal.



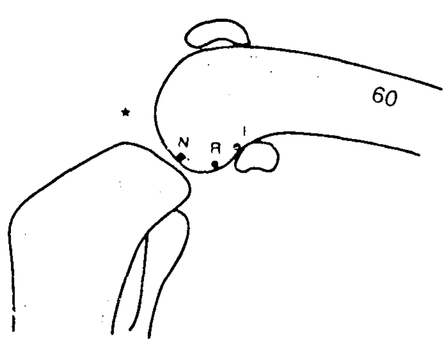


Figure 14

The mean instantaneous centres of rotation positions on the distal end of the left femur for the normal (N), injured (I), and repaired stifle (R). Also, the direction of movement at the point of contact of the normal stifle is given.

* ICR is located at contact point, therefore there is no velocity direction.

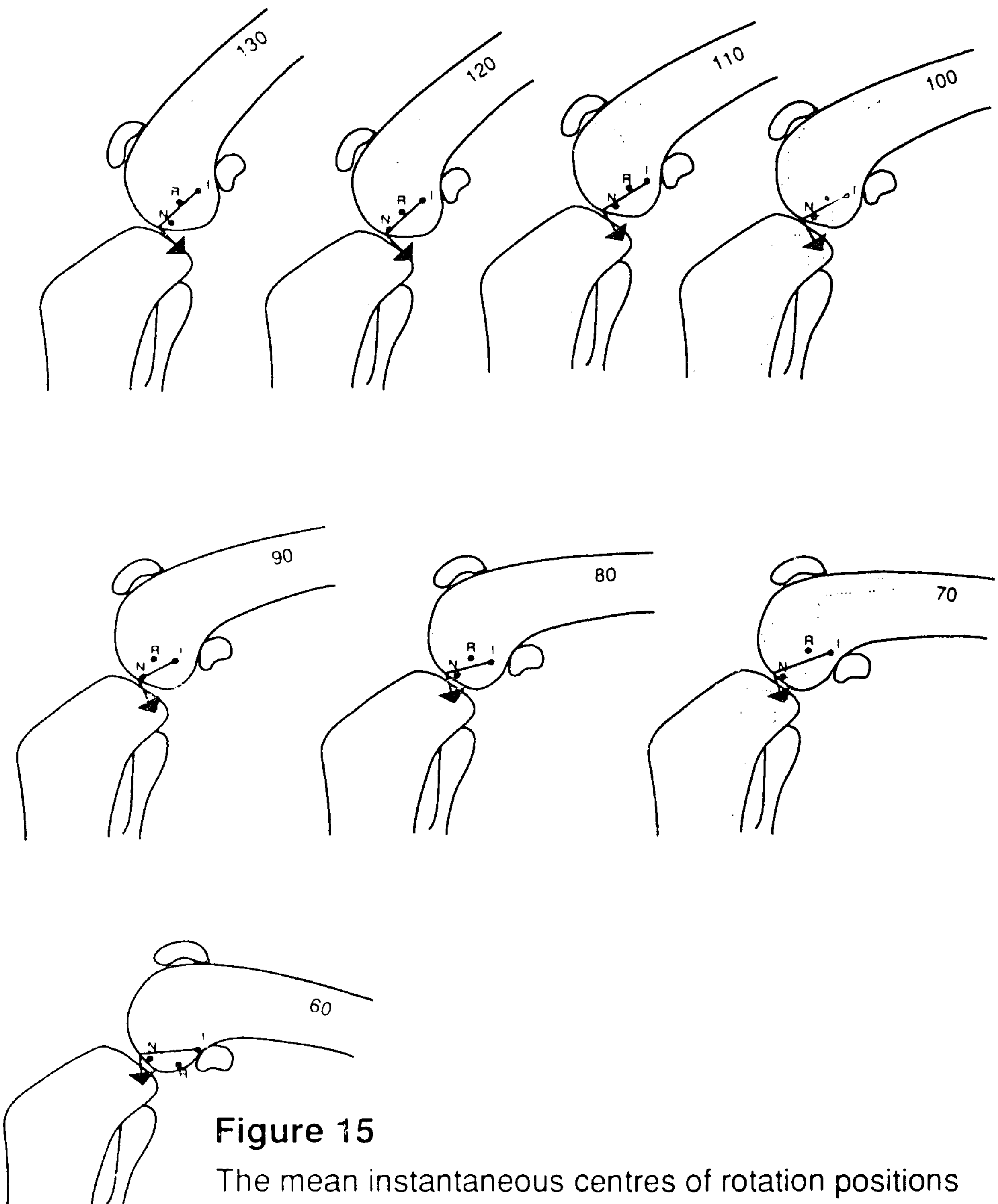


Figure 15

The mean instantaneous centres of rotation positions on the distal end of the left femur for the normal (N), injured (I), and repaired stifle (R). Also, the direction of movement at the point of contact of the stifle with cranial cruciate ligament rupture is given.

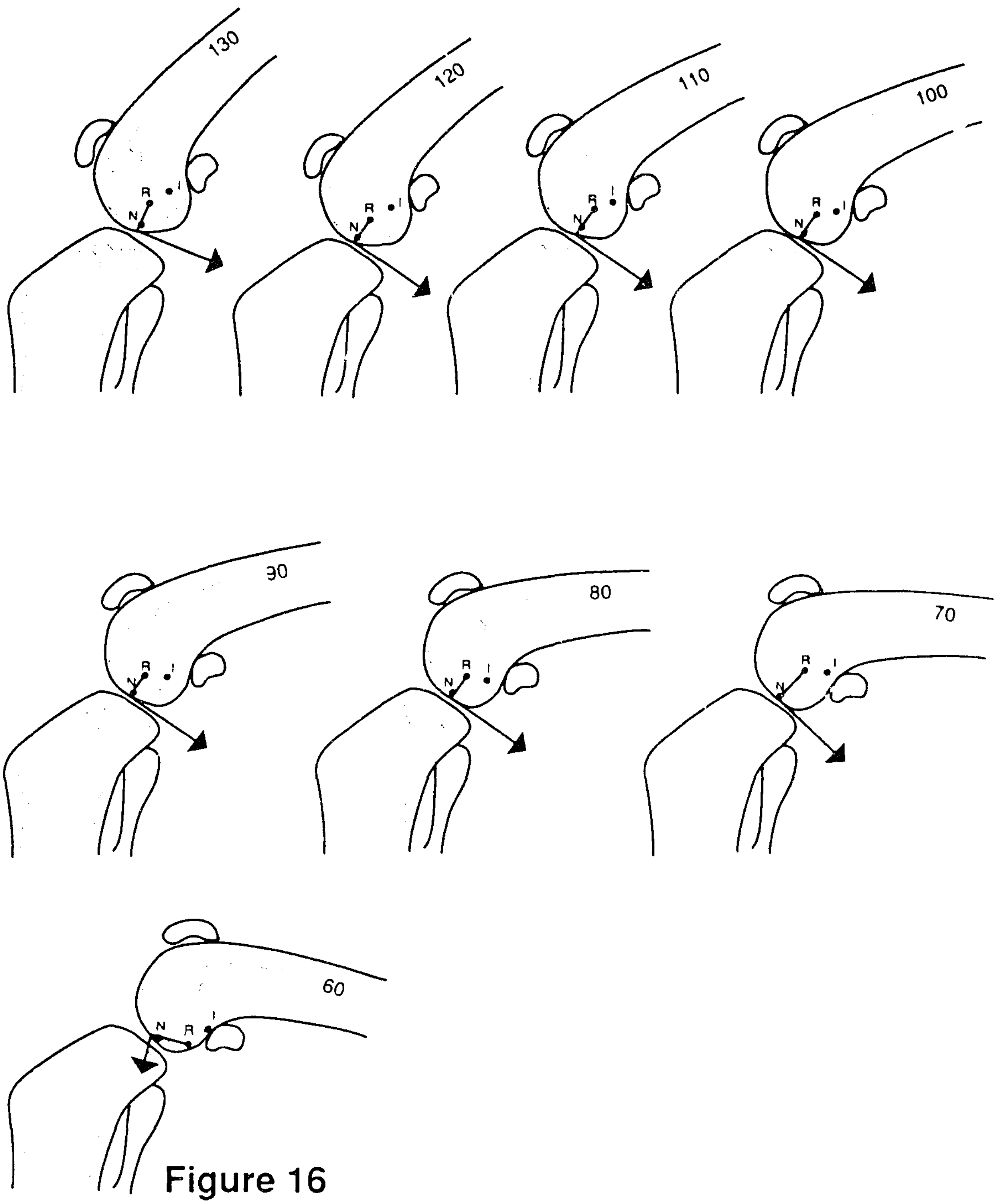


Figure 16

The mean instantaneous centres of rotation positions on the distal end of the left femur for the normal (N), injured (I), and repaired stifle (R). Also, the direction of movement at the point of contact of the stifle with the repaired cranial cruciate ligament is given.

The instantaneous centre in the injured stifle was displaced caudally and proximally from its normal position on or near the articular surface of the femoral condyle. The repair of the limb partially re-established the instantaneous centre of rotation to its normal location.

5. DISCUSSION

Rear limb lameness due to cranial cruciate ligament rupture is a common clinical problem. In this study the mean age of the dogs was 5.9 years, supporting the findings by Vasseur, P.B., et al. (54) of increased degeneration of the cranial cruciate ligament in dogs 5 years of age and over and naturally occurring cranial cruciate ligament ruptures. A number of surgical techniques have been developed to re-establish stifle joint stability lost following rupture of the cranial cruciate ligament. The success of most of these surgical methods of repair have been subjectively evaluated. The subjective evaluation criteria have included the cranial drawer sign, gait, postoperative lameness, and satisfaction of the clients (8, 22, 46, 46, 50). It was the objective of this study to use an accurate objective procedure to evaluate an intra-articular method (modified over-the-top technique) for the substitution of the cranial cruciate ligament.

Arnoczky et al. (17) used the instantaneous centre of rotation to evaluate an intra-articular and an extra-articular technique objectively for the repair of the cranial cruciate ligament of the canine stifle joint. He reported that the intra-articular technique tested did maintain normal motion at the contact point. However, following transection of the cranial cruciate ligament normal motion was apparently maintained at the point of contact. Arnoczky et al. explained that this result occurred because there was no craniocaudal force applied to the joint during the radiographic sessions. The lack of stress placed on the joint, and other errors in the technique accordingly reduced the accuracy of their technique.

In order to use the instantaneous centre of rotation for the evaluation of stifle joint injury and surgical repairs, there must be appropriate controls for comparing injured and repaired stifles. Ireland et. al. (32) compared instantaneous centres of rotation in left and right stifles of normal dogs and found there was no difference in instantaneous centre of rotation position between the right and left limbs of normal dogs. Therefore, the normal stifle joint can be used as a control for the contralateral joint when comparing instantaneous centres of rotation.

Arnoczky et al. (17) compared instantaneous centres of rotation positions in the normal limb before the cranial cruciate ligament was transected with the same limb after cranial cruciate ligament transection.

The present study optimized the accuracy of the results by taking into consideration the potential errors identified in the literature when finding the instantaneous centre of rotation for description of joint kinematics. The errors can be divided into parameters relative to the methods for taking the radiographic image, and the methods for measuring the radiographic image.

The method for locating the instantaneous centres of rotation positions employed in this study made use of an x-ray image intensifier. This enabled more accurate measurement of the different angles of flexion than conventional methods. The radiographic image was produced and recorded, then the different stifle angles were measured. In prior methods the stifle angles were approximated with a goniometer and then radiographs taken. With the increased accuracy in the angular measurements of the stifle angles, the instantaneous centre of rotation at specific angles of flexion for different treatment conditions can be compared with greater precision. This increase in accuracy of stifle angle measurement also increases the overall precision of this kinematic method.

Finally, to further reduce the error associated with taking the radiographic image, the joint movement was kept parallel to the x-ray film and the central x-ray beam was directed through the joint centre. This minimized the geometric distortion of the radiographic image.

Arnoczky et al. (17) attested that if the stifle was passively flexed the instantaneous centres of rotation positions in a ruptured cranial cruciate ligament stifle would not deviate from that of a normal stifle. The current study placed a cranial force of 35 newtons on the proximal end of the tibia. Neglecting the forces placed on the joint by the muscles, tendons, and ligaments, the cranial tibial thrust in a normal stifle bearing a weight of 37.7 kg (mean weight of dogs used in this study) is approximately 138 Newtons. It is believed that if a larger craniocaudal force than that used in the study was placed on the joint, the observed effect would be much more evident.

With respect to locating the instantaneous centre, a number of investigators have reported on parameters associated with taking measurements on a radiographic image (26, 27, 28, 29, 30). These studies provided means to adjust these parameters to increase the accuracy of the instantaneous centre positions. Rather than using the Rouleaux's vector method, a smooth curve was fitted through the marker point positions. This located the actual positions of the instantaneous centre of rotation more accurately (32).

Panjabi reported on a number of factors which could be adjusted to optimize the results in locating the instantaneous centres of rotation positions. These include the angle of rotation, the marker angle, and the distance between the estimated instantaneous centre of rotation and the marker points.

The angle of rotation used to find the instantaneous centre of rotation positions was 40°. This reduced the error due to small rotational angles described by Panjabi (26). The method used in this study chose the optimal marker angle (90°) described by Panjabi. Also, Panjabi's minimum limit of 20 mm between the estimated instantaneous centre of rotation and the marker points was exceeded in our procedure.

To increase the precision of the measurements appropriated from the radiographic images further, a high resolution digitizer was used and each coordinate was measured 5 times and averages were used for calculations.

Although the cranial drawer sign of the stifle joint may be within the normal range, the instantaneous centre of rotation pathway may be abnormal as evidenced by this study's repaired stifles (17). Thus, subjective evaluation using the cranial drawer sign could lead to a false conclusion that surgery was effective in restoring normal movement to the joint. The instantaneous centre of rotation describes the exact movement of the joint at every point of flexion or extension. Therefore, if the normal movement of the instantaneous centre of rotation pathway is re-established by surgery, the surgical procedure is considered effective.

The results show that cranial cruciate ligament rupture causes the instantaneous centre position to differ from the normal instantaneous centre position. Therefore, abnormal movement occurs between the articular surfaces in the injured stifle. The cranial cruciate ligament is the primary stabilizer preventing craniocaudal movement. Consequently, when the ligament is ruptured, the femur becomes caudally displaced with respect to the tibia. This was indicated in the current study by the significant caudal displacement of the instantaneous centre of rotation.

The over-the-top technique used to repair the cranial cruciate ligament in this investigation was augmented by a lateral and medial imbrication to alleviate a portion of the early postoperative stress placed on the graft. The nylon used for the imbrication can be expected to break or stretch within the first few postoperative weeks, thus the dogs were examined after 6-8 weeks so that the stabilizing influence of the imbrication sutures was minimized. Examination of the positions of the instantaneous centre of joint rotation at the different angulations in the repaired stifle revealed a restoration of near normal stifle movement after six weeks. The restoration in the craniocaudal direction was not complete but the trajectory of the repaired limb was within the normal range.

The instantaneous centre of rotation was also proximally displaced in the injured stifle compared to the normal stifle. The surgery did restore the instantaneous centre of rotation distally to within the normal range, but the restoration was not as complete as was found with craniocaudal movement.

All the instantaneous centre of rotation positions of the normal, injured, and repaired limbs between stifle angles of 130 and 60° were on the distal end of the femur. The positions of the instantaneous centre of rotation on the normal limb were found to be at or near the articular surface of the joint at all angulations. This indicates that there is predominantly a rolling motion of the femur on the tibia in the normal stifle (21). In the instances where the instantaneous centre of rotation was not exactly on the articular surface the movement at the point of joint contact was tangential or reasonably close to tangential to the surface. In this condition there is sliding motion with minimal friction between the articular surfaces (23).

Stifles with cranial cruciate ligament rupture showed a proximal displacement of the instantaneous centre of rotation away from the contact surface at all angulations. This indicates a sliding condition in the joint. Perpendiculars to the line drawn through the instantaneous centre of rotation were not tangential to the articular surface at the point of contact. Therefore, even with sliding taking place, there is an increase in the compressive and frictional forces in the injured stifle compared with the normal stifle (23). This internal derangement of the stifle usually results in arthritic changes such as meniscal lesions and abnormal wear of the articular cartilage (17, 23, 44, 50, 55).

The repaired limb showed a partial restoration of the instantaneous centre of rotation positions with less displacement from the articular surface. Thus less sliding is occurring for a particular angle of flexion in the repaired stifle than in the injured stifle. There is, however, more sliding in the repaired stifle than in the normal limb. However, unlike the condition in the injured stifle, the direction of movement in the repaired limb at the point of joint contact is tangential or approximately tangential. Therefore, in the repaired limb stifle, compression or separation was taking place when the stifle moved between angles of 130° and 80°. At a stifle angle of 70° there is a small amount of compression or separation and at 60° there appears to be a large amount of compression or separation in the repaired stifle. This indicates that the repair does not fully restore the joint to normal function.

Perhaps the kinematics of the repaired stifles were not fully re-established because of internal degenerative damage to other joint structures. Generally, in the case of cranial cruciate ligament ruptures, there is meniscal damage (57.9%) or some other type of stifle damage (26.6%) (50).

SAS

GENERAL LINEAR MODELS PROCEDURE

SCHEFFE'S TEST FOR VARIABLE: X

ALPHA=0.05 CONFIDENCE=0.95 DF=51
MSE=.0258117
CRITICAL VALUE OF F=3.17880

COMPARISONS SIGNIFICANT AT THE 0.05 LEVEL ARE INDICATED BY '***'

TREAT COMPARISON	SIMULTANEOUS LOWER CONFIDENCE LIMIT	DIFFERENCE BETWEEN MEANS	SIMULTANEOUS UPPER CONFIDENCE LIMIT
2 - 3	-0.02108	0.06341	0.14790
2 - 1	0.01760	0.10451	0.19142***
3 - 2	-0.14790	-0.06341	0.02108
3 - 1	-0.04492	0.04110	0.12711
1 - 2	-0.19142	-0.10451	-0.0176***
1 - 3	-0.12711	-0.04110	0.04492

SCHEFFE'S TEST FOR VARIABLE: Y

ALPHA=0.05 CONFIDENCE=0.95 DF=51 MSE=.0255524
CRITICAL VALUE OF F=3.17880

TREAT COMPARISON	SIMULTANEOUS LOWER CONFIDENCE LIMIT	DIFFERENCE BETWEEN MEANS	SIMULTANEOUS UPPER CONFIDENCE LIMIT
2 - 3	-0.02696	0.05711	0.14117
2 - 1	0.05528	0.14176	0.22823***
3 - 2	-0.14117	-0.05711	0.02696
3 - 1	-0.00093	0.08465	0.17023
1 - 2	-0.22823	0.14176	-0.05528***
1 - 3	-0.17023	-0.08465	0.00093

6. SUMMARY

In the present study, we utilized a procedure for evaluating surgical methods for joint repair and have given the results of applying the procedure. With this method the effectiveness of a modified over-the-top technique for cranial cruciate ligament substitution was determined. The ruptured cranial cruciate ligament displaced the instantaneous centre of rotation caudally and proximally with respect to the tibia. The modified over-the-top technique did restore the instantaneous centre caudally and distally with respect to the tibia (to within the normal limits), but the restoration was not complete.

The plots of the instantaneous centre of rotation positions on the femur for the different treatment conditions shows a predominantly rolling motion in the normal stifle, while the injured stifle has a sliding motion with compression or separation taking place. The surgery reduced the amount of sliding in the injured stifle joint and alleviated the compression or separation problem (between stifle angles of 30° and 80°). Some compression or separation continued to be a problem at stifle angles of between 70° and 60°.

7. **APPENDIX A.** - The X and Y coordinates of the instantaneous centres of rotation for the stifle joint of each dog with respect to treatment condition (normal = 1, cranial cruciate ligament ruptured = 2, cranial cruciate repaired = 3) and stifle angle (45^{0} = 1, 55^{0} = 2, 65^{0} = 3, 75^{0} = 4, 85^{0} = 5, 95^{0} = 6, 105^{0} = 7, 115^{0} = 8, 125^{0} = 9). Note, measurements given in inches.

Dog 1, sample 1

Treatment	Angle	X-coordinate	Y-coordinate
1	1	•	•
1	2	0.8441	0.4297
1	3	0.8380	0.3984
1	4	0.8772	0.4112
1	5	0.8550	0.2095
1	6	0.9515	0.4139
1	7	•	•
1	8	•	•
1	9	•	•
2	1	0.8319	0.5212
2	2	0.8280	0.4395
2	3	0.9083	0.3912
2	4	0.9632	0.3464
2	5	0.9789	0.4029
2	6	•	•
2	7	•	•
2	8	•	•
2	9	•	•
3	1	•	•
3	2	0.8088	0.4347
3	3	0.9166	0.3201
3	4	0.9639	0.3451
3	5	0.9217	0.3839
3	6	1.0289	0.6359
3	7	0.8431	0.4749
3	8	0.8903	0.3530
3	9	•	•

Dog 1, sample 2

Treatment	Angle	X-coordinate	Y-coordinate
1	1	•	•
1	2	0.83464	0.40455
1	3	0.83914	0.40471
1	4	0.06644	0.43161
1	5	0.87026	0.34183
1	6	0.91684	0.44046
1	7	•	•
1	8	•	•
1	9	•	•
2	1	0.82461	0.50347
2	2	0.81320	0.41917
2	3	0.85626	0.36389
2	4	0.93234	0.33786
2	5	0.96271	0.40161
2	6	•	•
2	7	•	•
2	8	•	•
2	9	•	•
3	1	•	•
3	2	0.84619	0.46467
3	3	0.91575	0.34310
3	4	0.96955	0.35872
3	5	0.90673	0.38421
3	6	0.94853	0.48912
3	7	0.91686	0.39751
3	8	0.90544	0.39463
3	9	•	•

Dog 2, sample 1

Treatment	Angle	X-coordinate	Y-coordinate
1	1	•	•
1	2	0.8386	0.3951
1	3	0.7564	0.2448
1	4	0.9083	0.2949
1	5	0.8878	0.3783
1	6	•	•
1	7	•	•
1	8	•	•
1	9	•	•
2	1	•	•
2	2	1.1222	0.8935
2	3	1.1025	0.6102
2	4	1.0409	0.5752
2	5	1.0012	0.4201
2	6	•	•
2	7	•	•
2	8	•	•
2	9	•	•
3	1	•	•
3	2	0.9673	0.3254
3	3	0.9503	0.4588
3	4	1.1238	0.4669
3	5	1.1364	0.2181
3	6	0.9823	0.1890
3	7	•	•
3	8	•	•
3	9	•	•

Dog 2, sample 2

Treatment	Angle	X-coordinate	Y-coordinate
1	1	•	•
1	2	0.90204	0.43355
1	3	0.80219	0.27006
1	4	0.90011	0.26104
1	5	0.98763	0.35758
1	6	•	•
1	7	•	•
1	8	•	•
1	9	•	•
2	1	•	•
2	2	1.16306	0.82073
2	3	1.12081	0.55683
2	4	0.93537	0.53389
2	5	0.91457	0.42180
2	6	•	•
2	7	•	•
2	8	•	•
2	9	•	•
3	1	•	•
3	2	0.94148	0.30874
3	3	0.93685	0.42977
3	4	1.09794	0.44107
3	5	1.08932	0.20695
3	6	0.93237	0.19701
3	7	•	•
3	8	•	•
3	9	•	•

Dog 3, sample 1

Treatment	Angle	X-coordinate	Y-coordinate
1	1	•	•
1	2	1.0932	0.5268
1	3	1.0274	0.4443
1	4	0.9527	0.4869
1	5	0.9963	0.5039
1	6	0.9582	0.3497
1	7	1.0355	0.4221
1	8	1.0811	0.4705
1	9	•	•
2	1	•	•
2	2	0.8800	0.0991
2	3	1.0697	0.5063
2	4	1.0997	0.7922
2	5	1.1459	0.9012
2	6	1.0112	0.5998
2	7	0.8246	0.4263
2	8	0.9103	0.1654
2	9	•	•
3	1	1.1069	0.8890
3	2	0.9374	0.5312
3	3	0.8327	0.4009
3	4	0.8434	0.5044
3	5	1.0328	0.4542
3	6	1.0100	0.4779
3	7	1.0323	0.4026
3	8	1.0532	0.4753
3	9	1.0738	0.5902

Dog 3, sample 2

Treatment	Angle	X-coordinate	Y-coordinate
	1	•	•
	2	0.90034	[illegible]92570
	3	1.06449	[illegible]28993
1	4	0.54047	
1	5	1.03071	0.45417
1	6	1.05999	0.59498
1	7	1.12282	0.74835
1	[illegible]	0.91120	0.38858
1	[illegible]	•	•
	1	•	•
2	2	0.82854	0.[illegible]3921
[illegible]	3	1.[illegible]1875	[illegible]47145
[illegible]		1.06106	0.82464
2		1.10246	1.02040
2		0.96551	0.52350
2	[illegible]	0.77252	[illegible]26928
2	8	0.86966	0.15739
[illegible]		•	•
3		1.12736	0.89656
3		0.89229	0.49977
3	3	0.88217	0.38861
3	4	0.88151	0.49491
3	5	[illegible]4702	0.46014
3	[illegible]	[illegible]8800	0.52869
3	7	1.06486	0.32394
3	[illegible]	1.25820	0.39844
[illegible]	9	1.20171	0.52762

Dog 4, sample 1

Treatment	Angle	X-coordinate	Y-coordinate
1	1	•	•
1	2	0.6249	0.6009
1	[illegible]	0.7561	0.4672
1	4	0.9045	0.3406
1	5	1.1224	0.3336
1	6	1.0579	0.2347
1	7	1.0095	0.1906
1	8	0.9979	0.2455
1	9	1.1083	0.2864
2	1	1.0073	0.3440
2	2	1.1625	0.5841
2	3	1.1296	0.5668
2	4	1.1655	0.6369
2	5	0.9953	0.7529
2	6	0.8855	0.6520
2	7	1.0234	0.5786
2	8	1.1378	0.4374
2	9	1.0301	0.2700
3	1	0.8506	0.5123
3	2	0.8643	0.5290
3	3	0.7663	0.4500
3	4	0.8060	0.4007
3	5	0.7595	0.3619
3	6	0.9635	0.3624
3	7	1.0069	0.4061
3	8	1.0076	0.5749
3	9	•	•

Dog 4, sample 2

Treatment	Angle	X-coordinate	Y-coordinate
1	1	•	•
1	2	0.76539	0.51872
1	3	0.84595	0.55376
1	4	0.84571	0.47984
1	5	0.77792	0.38774
1	6	0.74567	0.21148
1	7	0.75148	0.15202
1	8	0.79674	0.19075
1	9	0.92645	0.21431
2	1	0.82854	0.03921
2	2	1.01875	0.47145
2	3	1.06106	0.82464
2	4	1.10246	1.02040
2	5	0.96551	0.52350
2	6	0.77252	0.26928
2	7	0.86966	0.15739
2	8	3.65900	2.15800
2	9	3.09120	1.75110
3	1	0.93350	0.52490
3	2	0.85175	0.52298
3	3	0.71731	0.44341
3	4	0.71536	0.36483
3	5	0.77719	0.39567
3	6	0.97819	0.37514
3	7	0.98971	0.40751
3	8	0.97748	0.55285
3	9	•	•

Dog 5, sample 1

Treatment	Angle	X-coordinate	Y-coordinate
1	1	0.8749	0.3904
1	2	0.8182	0.3847
1	3	0.8618	0.4176
1	4	0.9452	0.3343
1	5	1.0147	0.3936
1	6	0.9451	0.3452
1	7	0.9350	0.3702
1	8	0.9324	0.2999
1	9	•	•
2	1	•	•
2	2	1.0739	0.6340
2	3	1.2186	0.6439
2	4	0.7314	1.1830
2	5	0.9675	0.9064
2	6	0.8757	0.7085
2	7	0.9573	0.4894
2	8	0.8596	0.2222
2	9	0.9070	0.2956
3	1	•	•
3	2	1.1562	0.4248
3	3	1.1284	0.4940
3	4	1.1198	0.643[illegible]
3	5	1.0715	0.6149
3	6	0.9864	0.5366
3	7	0.9667	0.6083
3	8	1.0146	0.4131
3	9	0.9950	0.1836

Dog 5, sample 2

Treatment	Angle	X-coordinate	Y-coordinate
1		0.91956	0.39056
1		0.77136	0.34572
1	3	0.80825	0.24128
1	4	1.03023	0.34566
1	5	1.04027	0.43525
1	6	0.97246	0.26918
	7	0.95530	0.29194
1	8	0.96648	0.30275
1	9	•	•
2	1	•	•
2	2	0.96884	0.47963
2	3	1.14380	0.45629
2	4	1.18360	0.58944
2	5	0.89870	0.72130
2	6	0.78734	0.59588
2	7	0.82634	0.38771
2	8	0.80646	0.18739
2	9	0.80864	0.25876
3	1	•	•
3	2	1.13478	0.30932
3	3	1.14042	0.49333
3	4	1.14271	0.65874
3	5	1.05904	0.80805
3	6	0.95160	0.69110
3	7	0.97800	0.54058
3	8	0.94318	0.29182
3	9	0.90310	0.12942

Dog 6, sample 1

Treatment	Angle	X-coordinate	Y-coordinate
1	1	•	•
1	2	0.7802	0.2807
1	3	0.8390	0.2215
1	4	0.8116	0.1878
1	5	0.9925	0.2756
1	6	•	•
1	7	•	•
1	8	•	•
1	9	•	•
2	1	•	•
2	2	0.8605	0.7338
2	3	0.8008	0.5520
2	4	1.0242	0.4788
2	5	1.1814	0.4766
2	6	1.1194	0.3703
2	7	0.8891	0.2737
2	8	•	•
2	9	•	•
3	1	•	•
3	2	•	•
3	3	0.8318	0.2853
3	4	1.1841	0.1811
3	5	1.0017	0.7416
3	6	0.7925	0.4983
3	7	•	•
3	8	•	•
3	9	•	•

Dog 6, sample 2

Treatment	Angle	X-coordinate	Y-coordinate
1	1	•	•
1	2	0.73986	0.26980
1	3	0.77783	0.32586
1	4	0.82576	0.22875
1	5	1.03995	0.29448
1	6	•	•
1	7	•	•
1	8	•	•
1	9	•	•
2	1	•	•
2	2	•	•
2	3	0.79594	0.78242
2	4	0.91085	0.51819
2	5	1.03464	0.38540
2	6	0.95302	0.25236
2	7	0.90487	0.27516
2	8	•	•
2	9	•	•
3	1	•	•
3	2	•	•
3	3	0.87013	0.37626
3	4	1.12597	0.48651
3	5	0.92835	0.73441
6	6	0.75016	0.44374
3	7	•	•
3	8	•	•
3	9	•	•

Dog 7, sample 1

Treatment	Angle	X-coordinate	Y-coordinate
1	1		
1	2	•	•
1	3	1.0105	0.7960
1	4	0.9698	0.6041
1	5	0.9057	0.4199
1	6	1.0666	0.3306
1	7	1.0726	0.2061
1	8	1.0632	0.2168
1	9	•	•
2	1	1.0541	0.4168
2	2	0.9162	0.3565
2	3	0.9239	0.3769
2	4	1.2078	0.6121
2	5	0.9733	0.4799
2	6	0.8327	0.3261
2	7	0.9654	0.2958
2	8	•	•
2	9	•	•
3	1	•	•
3	2	0.9313	0.7303
3	3	0.9192	0.6463
3	4	1.0752	0.5886
3	5	1.0392	0.3868
3	6	0.8642	0.7051
3	7	0.7051	0.3721
3	8	•	•
3	9	•	•

Dog 7, sample 2

Treatment	Angle	X-coordinate	Y-coordinate
1	1	•	•
1	2	•	•
1	3	0.86512	0.80819
1	4	1.00423	0.50025
1	5	0.73835	0.35976
1	6	1.07350	0.21638
1	7	0.90481	0.16007
1	8	0.94744	0.19656
1	9	•	•
2	1	1.07286	0.44316
2	2	0.93327	0.33066
2	3	0.92967	0.35116
2	4	1.15345	0.58402
2	5	0.94211	0.45488
2	6	0.90425	0.31677
2	7	0.93082	0.28076
2	8	•	•
2	9	•	•
3	1	•	•
3	2	0.80166	0.69916
3	3	0.87504	0.61887
3	4	1.02586	0.53433
3	5	1.02883	0.37447
3	6	0.89912	0.39556
3	7	0.72533	0.05393
3	8	•	•
3	9	•	•

8. APPENDIX B. - The upper and lower confidence limits for all possible comparisons for the x and y coordinates of the instantaneous centres among the treatments (normal = 1, cranial cruciate ligament ruptured = 2, cranial cruciate ligament repaired = 3), using Scheffe's test. Note, measurements given in inches.

9. **APPENDIX C.** - The upper and lower confidence limits for all possible comparisons for the x and y coordinates of the instantaneous centre of rotation among the different angulations ($45^0=1$, $55^0=2$, $65^0=3$, $75^0=4$, $85^0=5$, $95^0=6$, $105^0=7$, $115^0=8$, $125^0=9$) using Scheffe's test. Note, measurements given in inches.

SAS

GENERAL LINEAR MODELS PROCEDURE

ALPHA=0.05 CONFIDENCE=0.95 DF=51 MSE=.0258117
CRITICAL VALUE OF F=2.12602

COMPARISONS SIGNIFICANT AT THE 0.05 LEVEL ARE INDICATED BY '***'

RANGE COMPARISON	SIMULTANEOUS LOWER CONFIDENCE LIMIT	DIFFERENCE BETWEEN MEANS	SIMULTANEOUS UPPER CONFIDENCE LIMIT
9 - 8	-0.24326	0.11411	0.47148
9 - 4	-0.11269	0.21702	0.54673
9 - 5	-0.10454	0.22517	0.55488
9 - 1	-0.14936	0.25185	0.65306
9 - 6	-0.07202	0.26507	0.60215
9 - 7	-0.06888	0.27632	0.62152
9 - 3	-0.05029	0.27941	0.60912
9 - 2	-0.04027	0.29468	0.62963
8 - 9	-0.47148	-0.11411	0.24326
8 - 4	-0.14370	0.10291	0.34952
8 - 5	-0.13554	0.11106	0.35767
8 - 1	-0.19853	0.13775	0.47402
8 - 6	-0.10543	0.15096	0.40735
8 - 7	-0.10475	0.16221	0.42917
8 - 3	-0.08130	0.16531	0.41191
8 - 2	-0.07301	0.18057	0.43414
4 - 9	-0.54673	-0.2170	0.11269
4 - 8	-0.34952	-0.1029	0.14370
4 - 5	-0.19632	0.00815	0.21263
4 - 1	-0.27188	0.03483	0.34155
4 - 6	-0.16812	0.04805	0.26422
4 - 7	-0.16931	0.05930	0.28791
4 - 3	-0.14208	0.06239	0.26687
4 - 2	-0.13517	0.07766	0.29048
5 - 9	-0.55488	-0.22517	0.10454
5 - 8	-0.35767	-0.11106	0.13554
5 - 4	-0.21263	-0.00815	0.19632
5 - 1	-0.28003	0.02668	0.33339
5 - 6	-0.17627	0.03990	0.25607
5 - 7	-0.17746	0.05115	0.27976

RANGE COMPARISON		SIMULTANEOUS LOWER CONFIDENCE LIMIT	DIFFERENCE BETWEEN MEANS	SIMULTANEOUS UPPER CONFIDENCE LIMIT
5	- 3	-0.15023	0.05424	0.25872
5	- 2	-0.14332	0.06950	0.28233
1	- 9	-0.65306	-0.2518	0.14936
1	- 8	-0.47402	-0.13775	0.19853
1	- 9	-0.34155	-0.03483	0.27188
1	- 5	0.33339	-0.02668	0.28003
1	- 6	-0.30142	0.01321	0.32785
1	- 7	-0.29884	0.02447	0.34777
1	- 3	-0.27915	0.02756	0.33427
1	- 2	-0.26952	0.04282	0.35516
6	- 9	-0.60215	-0.2650	0.07202
6	- 8	-0.40735	-0.15096	0.10543
6	- 4	-0.26422	-0.04805	0.16812
6	- 5	-0.25607	-0.03990	0.17627
6	- 1	-0.32785	-0.01321	0.30142
6	- 7	-0.22788	0.01125	0.25038
6	- 3	-0.20182	0.01435	0.23052
6	- 2	-0.19448	0.02961	0.25369
7	- 9	-0.62152	-0.27632	0.06888
7	- 8	-0.42917	-0.16221	0.10475
7	- 4	-0.28791	-0.05930	0.16931
7	- 5	-0.27976	-0.05115	0.17746
7	- 1	-0.34777	-0.02447	0.29884
7	- 6	-0.25038	-0.01125	0.22788
7	- 3	-0.22552	0.00309	0.23170
7	- 2	-0.21775	0.01836	0.25446
3	- 9	-0.60912	-0.279411	0.05029
3	- 8	-0.41191	-0.16531	0.08130
3	- 4	-0.26687	-0.06239	0.14208
3	- 5	-0.25872	-0.05424	0.15023
3	- 1	-0.33427	-0.02756	0.27915
3	- 6	-0.23052	-0.01435	0.20182
3	- 7	-0.23170	-0.00309	0.22552
3	- 2	-0.19756	0.01526	0.22809
2	- 9	-0.62963	-0.29468	0.04027
2	- 8	-0.43414	-0.18057	0.07301
2	- 4	-0.29048	-0.07766	0.13517
2	- 5	-0.28233	-0.06950	0.14332
2	- 1	-0.35516	-0.04282	0.26952
2	- 6	-0.25369	-0.02961	0.19448
2	- 7	-0.25446	-0.01836	0.21775
2	- 3	-0.22809	-0.01526	0.1975

SAS

GENERAL LINEAR MODELS PROCEDURE

SCHEFFE'S TEST FOR VARIABLE: Y

ALPHA=0.05 CONFIDENCE=0.95 DF=51 MSE=.0255524
CRITICAL VALUE OF F=2.12602

COMPARISONS SIGNIFICANT AT THE 0.05 LEVEL ARE INDICATED BY '***'

RANGE COMPARISON		SIMULTANEOUS LOWER CONFIDENCE LIMIT	DIFFERENCE BETWEEN MEANS	SIMULTANEOUS UPPER CONFIDENCE LIMIT
4	- 1	-0.29566	0.00951	0.31468
4	- 5	-0.17938	0.02406	0.22751
4	- 2	-0.18415	0.02760	0.23935
4	- 3	-0.16860	0.03485	0.23829
4	- 9	-0.28000	0.04805	0.37609
4	- 6	-0.14411	0.07097	0.28605
4	- 8	-0.15988	0.08548	0.33085
4	- 7	-0.08447	0.14299	0.37045
1	- 4	-0.31468	-0.00951	0.29566
1	- 5	-0.29062	0.01455	0.31972
1	- 2	-0.29268	0.01809	0.32886
1	- 3	-0.27983	0.02534	0.33051
1	- 9	-0.36065	0.03854	0.43773
1	- 6	-0.25159	0.06146	0.37450
1	- 8	-0.25861	0.07597	0.41050
1	- 7	-0.18820	0.13348	0.45515
5	- 4	-0.22751	-0.02406	0.17938
5	- 1	-0.31972	-0.01455	0.29062
5	- 2	-0.20822	0.00354	0.21529
5	- 3	-0.19266	0.01079	0.21423
5	- 9	-0.30406	0.02398	0.35203
5	- 6	-0.16818	0.04690	0.26199
5	- 8	-0.18395	0.06142	0.30679
5	- 7	-0.10853	0.11893	0.34639
2	- 4	-0.23935	-0.02760	0.32415
2	1	-0.32886	-0.01809	0.29268
2	- 5	-0.21529	-0.00354	0.20822
2	- 3	-0.20451	0.00725	0.24353
2	- 9	-0.31282	0.20450	0.35371
2	- 6	-0.17959	0.04337	0.26632
2	- 8	-0.19441	0.05788	0.31018

RANGE COMPARISON	SIMULTANEOUS LOWER CONFIDENCE LIMIT	DIFFERENCE BETWEEN MEANS	SIMULTANEOUS UPPER CONFIDENCE LIMIT
2 - 7	-0.11953	0.11539	0.35031
3 - 4	-0.23829	-0.03485	0.16860
3 - 1	-0.33051	-0.02534	0.27983
3 - 5	-0.21423	-0.01079	0.19266
3 - 2	-0.21900	-0.00725	0.20453
3 - 9	-0.31485	0.01320	0.34125
3 - 6	-0.17896	0.03612	0.25120
3 - 8	-0.19473	0.05063	0.29600
3 - 7	-0.11932	0.10814	0.33560
9 - 4	-0.37609	-0.04805	0.28000
9 - 1	-0.43773	-0.03854	0.36065
9 - 5	-0.35203	-0.02398	0.30406
9 - 2	-0.35371	-0.02045	0.31282
9 - 3	-0.34125	-0.01320	0.31485
9 - 6	-0.31247	0.02292	0.35831
9 - 8	-0.31813	0.03744	0.39300
9 - 7	-0.24852	0.09494	0.43840
6 - 4	-0.28605	-0.07097	0.14411
6 - 1	-0.37450	-0.06146	0.25159
6 - 5	-0.26199	-0.04690	0.16818
6 - 4	-0.26632	-0.04337	0.17959
6 - 3	-0.25120	-0.03612	0.17896
6 - 9	-0.35831	-0.0229	0.31247
6 - 8	-0.24058	0.01452	0.26961
6 - 7	-0.16590	0.07202	0.30994
8 - 4	-0.33085	-0.08548	0.15988
8 - 1	-0.41055	-0.07597	0.25861
8 - 5	-0.30679	-0.06142	0.18395
8 - 2	-0.31018	-0.05788	0.19441
8 - 3	-0.29600	-0.05063	0.19473
8 - 9	-0.39300	-0.03744	0.31813
8 - 6	-0.26961	-0.01452	0.24058
8 - 7	-0.20811	0.05751	0.32312
7 - 4	-0.37045	-0.14299	0.08447
7 - 1	-0.45515	-0.13348	0.18820
7 - 5	-0.34639	-0.11893	0.10853
7 - 2	-0.35031	-0.11539	0.11953
7 - 3	-0.33560	-0.10814	0.11932
7 - 9	-0.43840	-0.09494	0.24852
7 - 6	-0.30994	-0.07202	0.16590
7 - 8	-0.32312	-0.05751	0.20811

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