Journal of Veterinary Science JVS

Original Article
Surgery

Check for updates

Patellofemoral contact mechanics after transposition of tibial tuberosity in dogs

Donghee Park [iD], Jinsu Kang [iD], Namsoo Kim [iD], Suyoung Heo [iD] *

Department of Veterinary Surgery, College of Veterinary Medicine, Jeonbuk National University, Iksan 54596, Korea

OPEN ACCESS

*Corresponding author:
Suyoung Heo
Department of Veterinary Surgery, College of Veterinary Medicine, Jeonbuk National University, 79 Gobong-ro, Iksan 54596, Korea.
E-mail: syheo@jbnu.ac.kr

ORCID iDs
Donghee Park [iD]
https://orcid.org/0000-0001-7316-5066
Jinsu Kang [iD]
https://orcid.org/0000-0001-5501-7983
Namsoo Kim [iD]
https://orcid.org/0000-0003-2160-1203
Suyoung Heo [iD]
https://orcid.org/0000-0002-7733-3263

Conflict of Interest
The authors declare no conflicts of interest.

Author Contributions
Conceptualization: Heo S, Kim N; Data curation: Park D, Kang J; Methodology: Park D, Kang J; Investigation: Park D, Kang J; Supervision: Heo S; Writing - original draft: Park D; Writing - review & editing: Kang J.

ABSTRACT

Background: Tibial tuberosity transposition (TTT) causes caudalization of the patellar ligament insertion in canine medial patellar luxation, which can lead to increases in patellofemoral contact pressure.

Objectives: The purpose of this study is to confirm the effect of patellofemoral contact mechanics after craniolateral and caudolateral transposition of tibial tuberosity in normal canine hindlimbs.

Methods: Craniolateral and caudolateral transposition of tibial tuberosity was performed in 5 specimens, respectively. The pressure was measured in the specimen before TTT, and then in the same specimen after TTT. In this process, data was obtained in 10 specimens. The measurement results were output as visualization data through the manufacturer's software and numerical data through spreadsheet. Based on these 2 data and the anatomical structure of the patellofemoral joint (PFJ) surface, whole measurement area was analysed by dividing into medial, lateral and central area.

Results: In craniolateralization of tibial tuberosity, total, medial, central contact pressure was decreased and lateral contact pressure was not statistically changed lateral contact pressure than normal PFJ. In caudolateralization of tibial tuberosity, total, lateral contact pressure was increased and medial contact pressure was not statistically changed than normal PFJ. Although not statistically significant changed, central contact pressure in caudolateralization of tibial tuberosity was increased in all 5 specimens.

Conclusions: These results imply that traditional TTT, prone to caudal shift of patellar tendon, can increase retropatellar pressure may lead to various complications and diseases of the stifle joint.

Keywords: Contact mechanics; dogs; patellar luxation; tibial tuberosity transposition

INTRODUCTION

Patellar luxation is one of the most frequent orthopedic diseases in canine hindlimb [1-3]. Medial patellar luxation (MPL) occurs at a rate of 75%–80% in affected dogs and lateral patellar luxation (LPL) commonly occurs in large breed dogs [1,4]. Malalignment of the quadriceps mechanism is recognized as the primary cause of patellar luxation [1]. These alterations cause abnormal loading and pressure distribution on articular surfaces of

patellofemoral joint (PFJ) [5,6]. Whereas the normally aligned patellar in growing dogs exerts physiological pressure on the trochlear groove for shaping adequate width and depth, abnormal pressure on the PFJ can lead to chondromalacia, subsequently resulting in osteoarthritis and pain [1-4,6,7].

Many surgical techniques exist to correct patellar luxation, including soft tissue reconstruction, trochleoplasty, distal femoral or proximal tibial corrective osteotomy, and tibial tuberosity transposition (TTT) [1,3,4,8]. Among these techniques, TTT is the only surgical option for realigning the quadriceps mechanism [1,3,4]. However, a previous study reported that traditional TTT causes caudalization of the patellar ligament insertion in canine MPL, which can lead to increases in patellofemoral contact pressure [3]. In human medicine, excessive patellofemoral contact pressure is considered a major cause of patellofemoral pain syndrome [9]. Fulkerson et al. introduced the oblique osteotomy of tibial tuberosity (TT) to anteromedial TTT in human LPL and several studies have demonstrated that this technique corrects patellar malalignment and reduces mean lateral and total contact pressure in a human LPL cadaveric model [6,10-12].

L'Eplattenier et al. [3] stated that traditional TTT is detrimental because of caudalization of the patellar ligament insertion, whereas craniolateralization of TT (CrLT) may be advantageous in terms of the contact mechanics of the PFJ in canine MPL. However, to the best of the author's knowledge, no experimental reports have described the effects on contact mechanics in the canine PFJ. This study was conducted to confirm the effects of caudolateralization of TT (CaLT), mimicking of caudal shift of the patellar ligament insertion after traditional TTT, and CrLT on the contact mechanics of the PFJ with a pressure distribution sensor in normal cadaveric canine stifles.

MATERIALS AND METHODS

Specimen preparation

Ten cadaveric hindlimbs were obtained from 5 adult dogs (retired military German shepherds) that were euthanatized for reasons unrelated to the study. Radiographic examination revealed no stifle joint lesions. The specimens were bilaterally disarticulated at the coxofemoral joint from each cadaver. All soft tissues of the specimens were dissected from the distal calcaneus to the proximal femur, except for the stifle, hook joint capsule, and collateral ligaments. The quadriceps muscle tendon was preserved approximately 1.5 cm from the proximal patella. Each specimen was submerged in 0.9% normal saline, wrapped in a plastic bag, and frozen at −80°C until the experiment was conducted.

In preparation for testing, the specimens were thawed at room temperature under moisture gauzes. The setting of the experimental model was modified from that described in previous studies [13-18]. Two 2.0-size K-wires were inserted mediolaterally and placed parallel at the mid-diaphyses of the femur, tibia, and calcaneus. The implanted K-wires were used as landmarks to angle the coxofemoral, stifle, and talocrural joints. A braided steel cable was penetrated into the quadriceps muscle tendon just above the proximal patella via a fabella needle, connected to a screw placed at the proximal femur with a turnbuckle, and sprung to mimic the quadriceps muscle mechanism. Another braided steel cable was passed between the bilateral fabella and the femoral condyle. After a hole was drilled at the proximal mid-point of the calcaneus using 2.5-size K-wire, another braided steel cable was passed through the hole. The 2 cables were mounted using an interposed turnbuckle to mimic the hamstring muscle mechanism.

The Pressure Distribution Measurement System (MC1509 Force Controller, MS9706 Sensor, Snowforce Visualization Software; Kitronyx Inc., Korea) was applied to measure the pressure on the PFJ. The system was composed of a force controller, sensor, and manufacturer's software. The sensor was 0.375 mm thick × 69 mm wide × 55 mm high, the pixel size was 1 mm × 1 mm, and the active sensing area was 24 mm × 24 mm. The pressure sensitivity range of the sensor was 3.16–25.29 psi. To insert the senor between the patella and the femoral trochlear groove, a bilateral parapatellar incision was made parallel to the patella. The sensor was fixed on the femur with two 18-mm, 1.5-size cortical screws (BS.COREM, Ltd., Korea).

Surgical procedure

TT was transposed in the craniolateral and caudolateral directions and then osteotomized and separated from the tibia by using an Electronic Oscillating Saw (PEDO-30W; OSADA Inc., USA). To achieve CrLT, the osteotomy line was placed between one-half of the tibial lateral aspect and the most medial point of the tibial cranial articular margin. To achieve CaLT, osteotomy was performed between the most lateral point of the tibial cranial articular margin and the mid-point of the tibial medial aspect on the plane of the proximal tibial plateau (**Fig. 1**). The 2 osteotomy procedures were continued until TT was completely separated from the tibia. The TT fragment was shifted craniolaterally or caudolaterally by
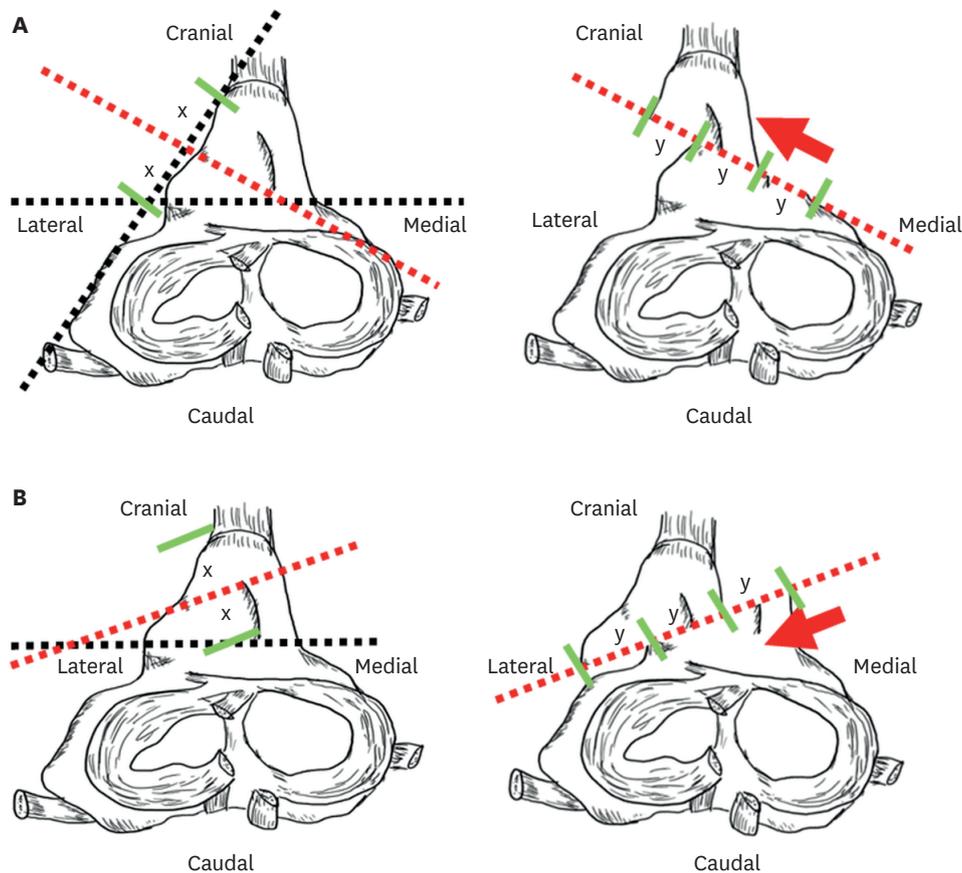

Fig. 1. Schematic illustration of CrLT in tibial plateau (A). Dashed red line is CrLT osteotomy line. Fragment of tibial tuberosity was moved craniolaterally by half osteotomy line (y). Schematic illustration of CaLT in tibial plateau (B). Dashed red line indicates CaLT osteotomy line. Fragment of tibial tuberosity was moved caudolaterally by half osteotomy line (y).
CrLT, craniolateralization of tibial tuberosity; CaLT, caudolateralization of tibial tuberosity.

half the width of each osteotomized plane and was stabilized using two 1.6-size K-wires and a 0.86-mm tension-band wire [8].

Experiment protocol and pressure measurement

The femoral head and great trochanter of the specimens were held in a customized jig by commercially available chemical injection cement. All specimens were placed in a normal canine stand phase. The angle between the femoral diaphysis and top side of the jig was set to 70° [13]. The customized jig was mounted on a Universal Testing Machine (WL2100C; Withlab Inc., Korea). The angle of the stifle and the talocrural joint was adjusted using each turnbuckle to 135° ± 5° and 145° ± 5°, respectively [13-15,17]. The marker pins inserted into the femur, tibia, and calcaneus bone were used to measure each joint angle with an electronic goniometer. The pressure on the PFJ was measured as a load of 30% body weight in the specimens according to the Universal Testing Machine [13-15,17]. To prevent slipping, commercially available sandpaper was attached to the contact area of the palmar pad (**Fig. 2**).

The pressure on the PFJ was measured in an untreated specimen and then in a specimen treated with TTT (CrLT or CaLT). During each TTT procedure, the pressure distribution sensor was not removed from the untreated specimens to maintain the same position. Each experiment lasted for 5 sec under a load of 30% body weight and repeated 5 times. The sensor data were visualized using a contact map and output to a spreadsheet after quantitative values were converted using the manufacturer's software (Snowforce; Kitronyx Inc.) (**Fig. 3**).

The magnitude of the pressure measured in the active sensing area of the sensor film was expressed as a numerical value in a specific cell of the spreadsheet indicating its position. The anatomical location corresponding to the sensor location was approximately separated by the distribution pattern of the numerical values represented in the spreadsheet. In this experiment, the active sensing area in the untreated specimens was divided according to the following criteria: 1) Top 10% of the recorded total numerical values were emphasized in the spreadsheet. 2) The emphasized numerical values were redistributed into 3 areas on the spreadsheet. 3) For data analysis, 2 straight lines were drawn along the running pattern of the medial or lateral trochlear ridge from the innermost values in the outermost 2 distribution areas, respectively. 4) The outermost 2 parts were defined as the medial area or the lateral

Fig. 2. The prepared specimens were mounted on Universal Testing Machine. The Sandpaper was attached on contact area of palmar pad to prevent slipping (red arrow). There is pressure distribution sensor in patellofemoral joint (blue arrowhead).
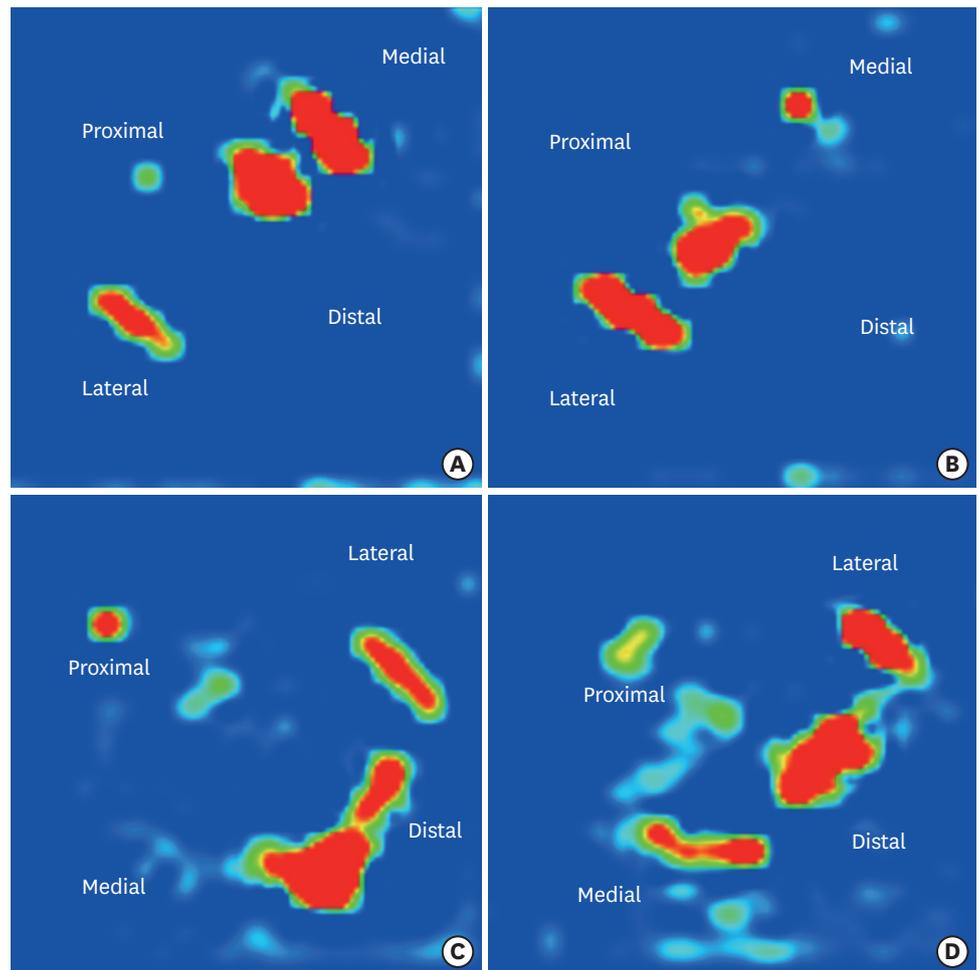
Fig. 3. The pressure distribution images of intact (A) and post-CrLT (B) specimen of PFJ. The pressure distribution images of intact (C) and post-CaLT (D) specimen of PFJ. The figures above are turned 45 degrees to the left when viewed from the front.
CrLT, craniolateralization of tibial tuberosity; CaLT, caudolateralization of tibial tuberosity; PFJ, patellofemoral joint.

area, depending on the right or left hindlimb, and the central part was defined as the central area. 5) All the procedures were performed in the above order in comparison with 3 areas of visual pressure map expressed by the manufacturer's software (Snowforce; Kitronyx Inc.). When TTT (CrLT or CaLT) was performed on the same specimen, the placement of the determined areas was left unchanged on the spreadsheet.

Measured values were processed as the total contact pressure, lateral or medial contact pressure, and central contact pressure in the spreadsheet. Total contact pressure (i.e., pressure on the PFJ) was defined as the sum of all measured values in the sensing area. Lateral or medial contact pressure (i.e., pressure on the lateral or medial trochlear ridge) was defined as the sum of measured values in the lateral or medial area. Central contact pressure (i.e., pressure on the patella) was defined as the sum of measured values in the central area. The values of untreated specimens were converted to 100. After each TTT (CrLT or CaLT), processed values were expressed as relative values for the untreated specimens. All data were presented as percentages of untreated specimens.

Statistical analysis

Statistical analyses were done with available software (SPSS 25.0; IBM Corp., USA). In this experiment, the data were sorted into 4 groups: untreated-CrLT, CrLT, untreated-CaLT, and CaLT. Data of each group were evaluated based on total contact pressure, lateral or medial contact pressure, and central contact pressure, and were expressed as the mean ± standard deviation. Comparisons between groups were performed as follows:

Comparison between untreated and the TTT groups, CrLT and CaLT, was performed using a paired-sample *t*-test. The mean values of untreated groups were set at 100%, whereas those of the TTT groups were expressed as relative values.

An independent-sample *t*-test was used for comparisons with the CrLT and CaLT groups. The mean values were presented relative to the corresponding untreated groups. Differences in the mean values were evaluated statistically in 2 groups.

For all statistical analyses performed, $p < 0.05$ was considered statistically significant.

RESULTS

Ten hindlimbs of 5 dogs were used in this experiment. The mean body weight of the 5 dogs was 35 kg (range, 28–39 kg). The angles of the stifle and talocrural joint were set at 135° ± 5° and 145° ± 5°, respectively, in all of the tests.

Total contact pressure decreased in the CrLT group (45.52% ± 25.36%, $p = 0.009$), whereas it increased in the CaLT group (110.53% ± 5.41%, $p = 0.012$) compared with the untreated group. Lateral contact pressure, described as pressure on the lateral trochlear ridge, increased in the CaLT group (138.41% ± 24.34%, $p = 0.024$), whereas it no significant change was observed in the CrLT group ($p = 0.265$) compared with the untreated group. Medial contact pressure decreased significantly in the CrLT group (35.31% ± 36.67%, $p = 0.017$), whereas no significant change was observed in the CaLT group ($p = 0.059$) compared with the untreated group. Central contact pressure, described as the pressure from the patella to the trochlear groove, increased in the CaLT group (154.42% ± 46.92%, $p = 0.06$), whereas it decreased in the CrLT group (51.82% ± 25.78%, $p = 0.014$) compared with the untreated group (**Fig. 4**).

Differences between the CrLT and CaLT groups in medial contact pressure were not statistically significant ($p = 0.151$). Total contact pressure (65.01% ± 11.59%, $p = 0.004$), lateral contact pressure (56.46% ± 17.67%, $p = 0.013$), and central contact pressure (102.60% ± 23.94%, $p = 0.005$) were significantly higher in the CaLT group than in the CrLT group (**Table 1**).

DISCUSSION

This study compared the contact mechanics of the PFJ in intact hindlimbs after CrLT and CaLT in a canine cadaveric model. Most of the results of this study confirmed differences in the patellofemoral pressure distribution depending on CrLT and CaLT.
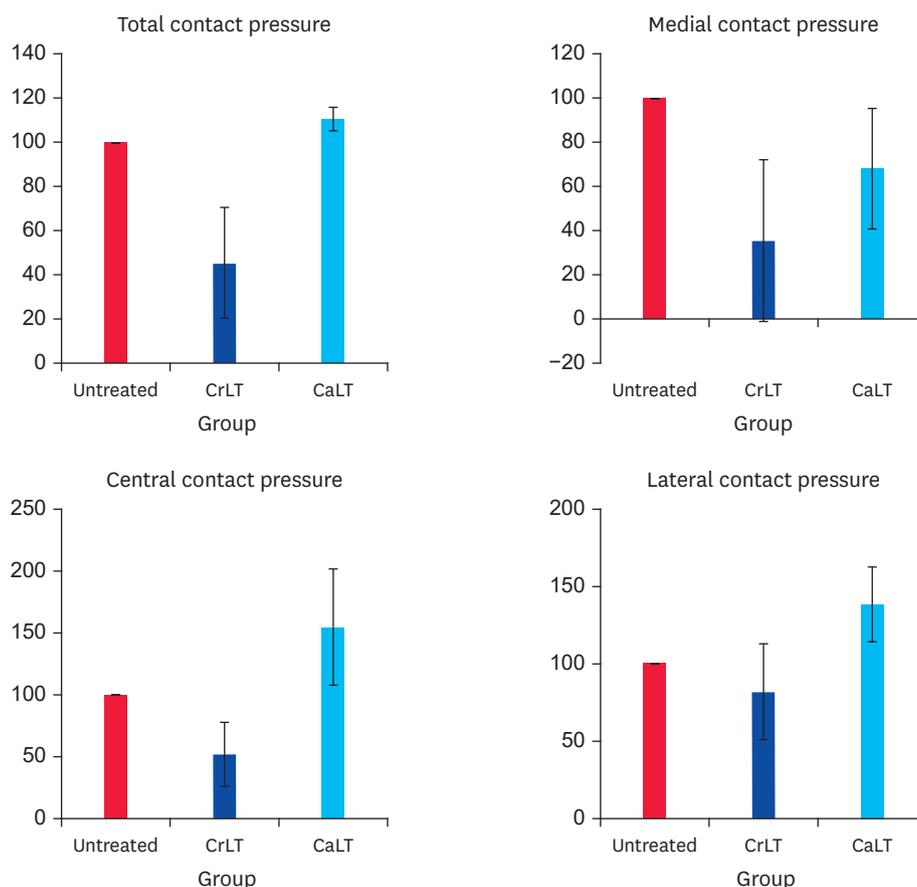
Fig. 4. A Pressure distribution data of Untreated, CrLT and CaLT group in PFJ after converting into a percentage. CrLT, craniolateralization of tibial tuberosity; CaLT, caudolateralization of tibial tuberosity; PFJ, patellofemoral joint.

Table 1. A comparative data between CrLT and CaLT group on pressure distribution in PFJ after converting into percentage

Parameter (%)	CrLT–CaLT group
Total contact pressure	65.01 ± 11.59 (p = 0.004)
Medial contact pressure	32.70 ± 20.44 (p = 0.151)
Central contact pressure	102.60 ± 23.94 (p = 0.005)
Lateral contact pressure	56.46 ± 17.67 (p = 0.013)

Statistically significant p values are bolded (p value < 0.05).
CrLT, craniolateralization of tibial tuberosity; CaLT, caudolateralization of tibial tuberosity; PFJ, patellofemoral joint.

Previous experimental studies have demonstrated that mechanical load causes direct degeneration of articular cartilage in affected compartments in humans, dogs, and cats [19]. Additionally, Ryu et al. [20] experimentally identified that changes in articular cartilage occurred in the patellar lateral facets, with shearing at the highest pressure, in an *in vivo* induced-Lateral Patellar Subluxation rabbit model. In human medicine, anteromedialization of TT has been performed both to treat LPL and prevent pre- or post-operative patellofemoral pain [6,7,10-12]. However, to the best of the author's knowledge, changes in PFJ pressure distribution have not yet been thoroughly considered in pre-, peri-, and post-TTT procedures in veterinary medicine.

The objective of TTT is normally to realign the extensor mechanism, which results in appropriate distribution of contact stress in the PFJ [3]. Lara et al. [2] stated that erosion

of the medial femoral condyle and the lateral patellar surface results from friction on the articular surface in canine dogs. In other words, another crucial role of TTT is to reduce pressure on the medial or lateral trochlear ridge in patellar luxation. In the present study, medial contact pressure in the CrLT group decreased by approximately 35%, whereas no significant change was observed in the CaLT group compared with the untreated hindlimb group. The results of the CaLT group may have been due to insufficient patellar lateral shift with either a decreased moment arm of the patellar tendon or patellar lateral tilt on the femoral trochlear groove. Conversely, the opposite conditions may result in intended lateral shift after CrLT [14,21]. These results indicate that reduction of medial contact pressure following CrLT may be beneficial in relieving pain induced by MPL [2,22,23].

In human medicine, many studies have reported that excessive mechanical load can directly damage the articular surface, sequentially degenerating chondrocyte function in terms of repair capacity and leading to arthritis and pain [24-26]. To the best of the author's knowledge, no clinical or experimental studies have been conducted with dogs to determine the relationship between mechanical pressure and pain, assess whether TTT increases pressure on the PFJ compared with normal hindlimbs, and accurately predict detrimental effects [3]. Towle et al. [27] used radiographic and computed tomographic techniques to assess canine MPL and identified that traditional TTT leads to caudalization of the patellar tendon insertion, and stated that it may be due to the lack of an appositional plane between fragments of TT and the recipient bed. In human medicine, this condition is known as Wyberg's syndrome, which was referred to as CaLT in the present study [3]. In this study, as L'Eplattenier et al. [3] speculated, CaLT led to higher central and lateral contact pressure compared with the untreated hindlimbs. Conversely, CrLT resulted in decreased central contact pressure and did not significantly change lateral contact pressure compared with the untreated hindlimbs. Clinically, although recentering the extensor mechanism and patella as intended, traditional TTT can cause postoperative pain because of additional damage to the femoral trochlear groove, femoral lateral trochlear ridge, or patella, particularly in PFJ with osteoarthritis or chondromalacia [27].

Total contact pressure is the sum of medial, central, and lateral compartment pressure. Elevation of total contact pressure in CaLT resulted from the lack of significant changes in medial contact pressure, increased lateral contact pressure, and, despite the lack of statistical significance, increased central pressure in all specimens. This result supports the notion that caudal shift of the patellar tendon insertion increases patellofemoral contact pressure, as described in a previous report [3]. Decreased of total contact pressure in CrLT resulted from decreased medial contact pressure and central contact pressure, and the lack of significant change in lateral contact pressure. This finding is similar to those of Beck et al, who identified that anteromedialization of the tibial tubercle reduces mean lateral and total contact pressure in a human cadaveric model used to hypothesize human LPL [10].

Various surgical methods have been combined to correct patellar luxation in dogs [1,3,4,8,27,28], one of which is femoral trochlear deepening, including trochlear sulcoplasty, chondroplasty, and wedge and block recession [1,3,4,8,28]. Arthurs et al stated that the combination of TTT with trochlear sulcoplasty reduces patellar reluxation and postoperative complications [29]. However, other studies have reported that all femoral trochlear deepening damages the hyaline cartilage on the articular surface and leads to the release of protease, subsequently contributing to progressive osteoarthritis [28,30]. In this

regard, traditional TTT likely plays a role in accelerating the progression of postoperative osteoarthritis on the articular surface with femoral trochlear deepening.

L'Eplattenier et al. [3] reported that the advantages of CrLT are that it allows a much larger bone surface of the recipient because of oblique caudal osteotomy of TT, and it avoids damaging the medial meniscus and tendon of the long digital extensor muscle. However, a human study reported that anteromedialization of TT for LPL cannot reconstruct normal patellar tilt or shift in the transverse plane [6]. Hence, care should be taken when extrapolating the superiority of CrLT from these results. Therefore, additional studies should be performed on canine patellar kinematics with varying shift, tilt, and rotation after CrLT and traditional TTT [21].

This study had several limitations. The cadaveric canine stifle model was modified from a previous *ex vivo* model for cranial cruciate ligament deficient stifle in dogs and cats [13-18]. Although this model reproduced the quadriceps and hamstring muscle mechanism in a standing posture for canine stifles *in vivo*, it cannot fully represent all elements, including passive and active stabilizers [18]. Moreover, dissection of additional joint capsules was necessary to insert the pressure distribution sensor and perform the TTT procedures in the stifle joint [31]. In this model, maintaining the angles of the stifle and tarsocrural joint at 135° ± 5° and 145° ± 5°, respectively, was difficult, and adjustment of the flexion angle resulted in unstable apparatus, as described in previous studies [13,15,18]. Hence, evaluation of diverse flexion angles was restricted in this study.

The author used a film-based pressure distribution sensor. This sensor has similar reusability and flexibility as sensors used in previous studies [10,12,14,31]. However, the author found difficulty in fixing the sensor to the femoral trochlear and avoiding crinkling of the sensor because of the slippery and irregular articular surface. These problems may have influenced the validity of the data and caused artifacts. Previous studies have sutured the sensor to the surrounding soft tissue of the stifle to fix the sensor to the femoral surface [10,32-34]. In this study, to improve conformity, the author secured the sensor with 2 screws on the distal femoral diaphysis and, to minimize crinkling, used a new sensor for each specimen. Nevertheless, slipping and crinkling of the senor could not be completely avoided.

Because the specimens were normal hindlimb, this study cannot represent the biomechanical environment of MPL hindlimbs, including distal femoral varus or valgus, torsion of the distal femur, proximal tibial varus or valgus, tibial torsion, deviation of the quadriceps mechanism, and a shallow femoral trochlear groove [1,27]. In addition, this study had the same limitations as other cadaveric experimental studies, which cannot simulate *in vivo* dynamic biomechanical environments during activity [24]. Nevertheless, because the contact mechanics of the stifle joint cannot be measured *in vivo*, these results may provide useful information about differences in contact mechanics after CrLT and traditional TTT. In human medicine, because patellar kinematics has major effect on contact mechanics in the PFJ, many studies have already evaluated kinematics as well as the contact mechanics of the PFJ after realignment of TT [6,12,32,34]. Therefore, these results should be interpreted carefully.

In conclusion, CrLT reduced medial contact pressure without increasing contact pressure on other sections. However, CaLT did not significantly reduce the medial contact pressure, but rather increased lateral contact pressure in the intact cadaveric stifle model. These results imply that traditional TTT, which is prone to caudal shift of the patellar tendon, can cause postoperative complications including chondromalacia and arthritis, as well as being unable

to definitively resolve pathologic conditions or clinical signs caused by MPL. Although further study on additional dynamic movements and kinematics of the patella are required to evaluate the biomechanical effects of each type of TTT on the PFJ, CrLT may have the advantage of preventing postoperative complications and effectively relieving clinical signs more effectively than traditional TTT in regards to contact mechanics in canine MPL.

REFERENCES

1. Di Dona F, Della Valle G, Fatone G. Patellar luxation in dogs. Vet Med (Auckl). 2018;9:23-32.
   PUBMED | CROSSREF

2. Lara J, Alves EG, Oliveira HP, Varón JA, Rezende CM. Patellar luxation and articular lesions in dogs: a retrospective: study research article. Arq Bras Med Vet Zootec. 2018;70:93-100.
   CROSSREF

3. L'Eplattenier H, Montavon P. Patellar luxation in dogs and cats: management and prevention. Compend Contin Educ Pract Vet. 2002;24:292-298.

4. Pérez P, Lafuente P. Management of medial patellar luxation in dogs: what you need to know. Vet Irel J. 2014;4:634-640.

5. Iliadis AD, Jaiswal PK, Khan W, Johnstone D. The operative management of patella malalignment. Open Orthop J. 2012;6(1):327-339.
   PUBMED | CROSSREF

6. Ramappa AJ, Apreleva M, Harrold FR, Fitzgibbons PG, Wilson DR, Gill TJ. The effects of medialization and anteromedialization of the tibial tubercle on patellofemoral mechanics and kinematics. Am J Sports Med. 2006;34(5):749-756.
   PUBMED | CROSSREF

7. Steimer O, Kohn D. Anteromedialization of the tibial tubercle. Oper Tech Orthop. 2007;17(1):66-71.
   CROSSREF

8. Johnston SA, Tobias KM. *Veterinary Surgery: Small Animal Expert Consult: 2-Volume Set*. Philadelphia: Saunders; 2017.

9. Waryasz GR, McDermott AY. Patellofemoral pain syndrome (PFPS): a systematic review of anatomy and potential risk factors. Dyn Med. 2008;7:9.
   PUBMED | CROSSREF

10. Beck PR, Thomas AL, Farr J, Lewis PB, Cole BJ. Trochlear contact pressures after anteromedialization of the tibial tubercle. Am J Sports Med. 2005;33(11):1710-1715.
    PUBMED | CROSSREF

11. Fulkerson JP. Anteromedialization of the tibial tuberosity for patellofemoral malalignment. Clin Orthop Relat Res. 1983;(177):176-181.
    PUBMED | CROSSREF

12. Saranathan A, Kirkpatrick MS, Mani S, Smith LG, Cosgarea AJ, Tan JS, et al. The effect of tibial tuberosity realignment procedures on the patellofemoral pressure distribution. Knee Surg Sports Traumatol Arthrosc. 2012;20(10):2054-2061.
    PUBMED | CROSSREF

13. Apelt D, Kowaleski MP, Boudrieau RJ. Effect of tibial tuberosity advancement on cranial tibial subluxation in canine cranial cruciate-deficient stifle joints: an *in vitro* experimental study. Vet Surg. 2007;36(2):170-177.
    PUBMED | CROSSREF

14. Guerrero TG, Pozzi A, Dunbar N, Kipfer N, Haessig M, Beth Horodyski M, et al. Effect of tibial tuberosity advancement on the contact mechanics and the alignment of the patellofemoral and femorotibial joints. Vet Surg. 2011;40(7):839-848.
    PUBMED | CROSSREF

15. Hoffmann DE, Kowaleski MP, Johnson KA, Evans RB, Boudrieau RJ. *Ex vivo* biomechanical evaluation of the canine cranial cruciate ligament-deficient stifle with varying angles of stifle joint flexion and axial loads after tibial tuberosity advancement. Vet Surg. 2011;40(3):311-320.
    PUBMED | CROSSREF

16. Kipfer NM, Tepic S, Damur DM, Guerrero T, Hässig M, Montavon PM. Effect of tibial tuberosity advancement on femorotibial shear in cranial cruciate-deficient stifles. An *in vitro* study. Vet Comp Orthop Traumatol. 2008;21(5):385-390.
    PUBMED | CROSSREF

17. Pozzi A, Kim SE, Conrad BP, Horodyski M, Banks SA. *Ex vivo* pathomechanics of the canine Pond-Nuki model. PLoS One. 2013;8(12):e81383.
PUBMED | CROSSREF

18. Retournard M, Bilmont A, Asimus E, Palierne S, Autefage A. Effect of tibial tuberosity advancement on cranial tibial subluxation in the feline cranial cruciate deficient stifle joint: an *ex vivo* experimental study. Res Vet Sci. 2016;107:240-245.
PUBMED | CROSSREF

19. Clark AL, Barclay LD, Matyas JR, Herzog W. In situ chondrocyte deformation with physiological compression of the feline patellofemoral joint. J Biomech. 2003;36(4):553-568.
PUBMED | CROSSREF

20. Ryu J, Saito S, Yamamoto K. Changes in articular cartilage in experimentally induced patellar subluxation. Ann Rheum Dis. 1997;56(11):677-681.
PUBMED | CROSSREF

21. Loudon JK. Biomechanics and pathomechanics of the patellofemoral joint. Int J Sports Phys Ther 2016;11(6):820-830.
PUBMED

22. Huber J, Gasser B, Perren SM, Bandi W. Changes in retropatellar pressure values in relation to the position of the tibial tuberosity. Knee. 1994;1:S19-S43.
CROSSREF

23. Martinez SA. Congenital conditions that lead to osteoarthritis in the dog. Vet Clin North Am Small Anim Pract. 1997;27(4):735-758.
PUBMED | CROSSREF

24. Heijink A, Gomoll AH, Madry H, Drobnič M, Filardo G, Espregueira-Mendes J, et al. Biomechanical considerations in the pathogenesis of osteoarthritis of the knee. Knee Surg Sports Traumatol Arthrosc. 2012;20(3):423-435.
PUBMED | CROSSREF

25. Musumeci G. The effect of mechanical loading on articular cartilage. J Funct Morphol Kinesiol. 2016;1(2):154-161.
CROSSREF

26. Sun HB. Mechanical loading, cartilage degradation, and arthritis. Ann N Y Acad Sci. 2010;1211(1):37-50.
PUBMED | CROSSREF

27. Towle HA, Griffon DJ, Thomas MW, Siegel AM, Dunning D, Johnson A. Pre- and postoperative radiographic and computed tomographic evaluation of dogs with medial patellar luxation. Vet Surg. 2005;34(3):265-272.
PUBMED | CROSSREF

28. Linney WR, Hammer DL, Shott S. Surgical treatment of medial patellar luxation without femoral trochlear groove deepening procedures in dogs: 91 cases (1998–2009). J Am Vet Med Assoc. 2011;238(9):1168-1172.
PUBMED | CROSSREF

29. Arthurs GI, Langley-Hobbs SJ. Complications associated with corrective surgery for patellar luxation in 109 dogs. Vet Surg. 2006;35(6):559-566.
PUBMED | CROSSREF

30. Roy RG, Wallace LJ, Johnston GR, Wickstrom SL. A retrospective evaluation of stifle osteoarthritis in dogs with bilateral medial patellar luxation and unilateral surgical repair. Vet Surg. 1992;21(6):475-479.
PUBMED | CROSSREF

31. Stephen J, Alva A, Lumpaopong P, Williams A, Amis AA. A cadaveric model to evaluate the effect of unloading the medial quadriceps on patellar tracking and patellofemoral joint pressure and stability. J Exp Orthop. 2018;5(1):34.
PUBMED | CROSSREF

32. Ostermeier S, Holst M, Hurschler C, Windhagen H, Stukenborg-Colsman C. Dynamic measurement of patellofemoral kinematics and contact pressure after lateral retinacular release: an *in vitro* study. Knee Surg Sports Traumatol Arthrosc. 2007;15(5):547-554.
PUBMED | CROSSREF

33. Rue JP, Colton A, Zare SM, Shewman E, Farr J, Bach BR Jr, et al. Trochlear contact pressures after straight anteriorization of the tibial tuberosity. Am J Sports Med. 2008;36(10):1953-1959.
PUBMED | CROSSREF

34. Stephen JM, Lumpaopong P, Dodds AL, Williams A, Amis AA. The effect of tibial tuberosity medialization and lateralization on patellofemoral joint kinematics, contact mechanics, and stability. Am J Sports Med. 2015;43(1):186-194.
PUBMED | CROSSREF