Evaluation of tibiotarsal transarticular immobilization techniques and kinematic study of the gastrocnemius muscle-tendon unit in dogs

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Abstract:

The common calcaneal tendon is a complex muscle-tendon system that regulates flexion/extension of the tibiotarsal joint motion as well as the phalanges. Common calcaneal tendon injury is not uncommon, and two types of injuries are recognized: acute or chronic. Acute injuries are usually related to trauma by a sharp object, transecting skin and underlying structures, including tendons. No definitive causes of chronic injury have been identified, but middle age, large-breed dogs are more predisposed to be affected.

The treatment of common calcaneal tendon injury consists of debridement, anastomosis and temporary tibiotarsal joint immobilization during tendon healing. Acute traumatic common calcaneal tendon injury is managed in a very similar way for each patient. Several types of immobilization technique have been described, however, no optimal immobilization technique that neutralizes tension in the common calcaneal tendon has been identified. Numerous biomechanical studies of common calcaneal tendon repairs are reported in human and animal models. In human patients, early controlled motion minimizes various complications, resulting in better outcomes. However, there is no gold standard postoperative protocol for veterinary patients. It can be problematic in veterinary patients to control patient activity and have good client and patient compliance. In this research project, six tibiotarsal transarticular fixation methods were evaluated, and a kinematic evaluation of the gastrocnemius tendon was performed at various femorotibial and tibiotarsal joint angle combinations. These data will help inform development of an optimal immobilization method during healing of common calcaneal tendon injury in dogs.
Declaration:

This is to certify that:

I. The thesis comprises only my original work towards the Masters.

II. Due acknowledgement has been made in the text to all other material used.

III. The thesis is less than 20,000 words in length, exclusive of tables and appendices.

Takanori Sugiyama    Date: 01/02/2018
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List of Abbreviations

CCT – common calcaneal tendon

CGa – calcaneogastrocnemius angle

CR – center of rotation

CT – conjoined tendon or accessory tendon (AT)

ESF – external skeletal fixation

FFa – femorofabellar angle

FGa – fabellogastrocnemius angle

FFL – femorofabellar length

FTJ – femorotibial joint

GMTU – gastrocnemius muscle-tendon unit

GT – gastrocnemius tendon

N - Newton

ROM – range of motion

SDFT – superficial digital flexor tendon

TCa – tibiocalcaneal angle

TCL – talocalcaneal length

TTJ – tibiotalarsal joint
1 Introduction:

1.1 Background:
Common calcaneal tendon (CCT) injuries occur in dogs and humans, causing significant functional impairment to the leg and tibiotarsal region. Treatment options can be conservative or surgical. Tendon healing is slow relative to many other tissues due to relatively poor vascular supply. Tendons never regain 100% of their pre-injury tensile strength. During recovery, temporary immobilization of the tibiotarsal joint is required to decrease strain in the tendon to prevent gap formation. This immobilization can cause significant morbidity in the joint, and can affect the tensile strength and duration of the healing of the tendon.

1.2 Anatomy and individual tendon component functions:
A tendon consists of dense collagen-rich fibers that connect a muscle to a bone.\textsuperscript{1} The functions of tendons are to transfer the force of muscular contraction to the skeleton. The CCT is an energy storing tendon, which has greater elastic fiber content and is adapted to respond to the forces of weight bearing by energy storage and elastic recoil.\textsuperscript{2} The site of bone attachment of a tendon is highly fibrous or fibrocartilaginous, known as entheses. This forms an osteotendinous attachment, providing a transition zone between a tendon and a bone.\textsuperscript{3} The tendon of the gastrocnemius muscle is believed to be the main part of the Achilles mechanism. However, a recent study has described comparison of the tensile load of the gastrocnemius tendon (GT) and superficial digital flexor tendon (SDFT) at their proximal and distal sections (Figure 1-3).\textsuperscript{4}

The anatomy and function of the canine hind limb muscles have been well described.\textsuperscript{5} The CCT (also called the Achilles tendon) consists of three independent tendons: the gastrocnemius tendon (GT), superficial digital flexor tendon (SDFT), and conjoined tendons (CT or accessory tendon; AT).
1. Gastrocnemius tendon (GT):

The gastrocnemius muscle is divided into two bellies: the medial and lateral heads which originate from the medial and lateral fabellae and supracondylar tuberosities,
respectively. The GT inserts on to the tuber calcanei. The function of the gastrocnemius muscle is flexion of the femorotibial joint and extension of the tibiotarsal joint.

2. Superficial digital flexor tendon (SDFT):

The origin of the SDF muscle is the lateral supracondylar tuberosity of the femur and the lateral fabella (sharing the origin with the lateral gastrocnemius muscle). The SDF muscle sits between the medial and lateral heads of gastrocnemius muscles. Proximally the SDFT runs craniomedially relative to the medial head of the gastrocnemius muscle. Distally, the SDFT crosses over the GT mediocaudally (more superficially), flattened and widened to form the CCT with other tendons. The SDFT continues distally to insert at the planter surface of the second phalanges to flex digits. Other functions of the SDF muscle including extension and flexion of tibiotarsal joint and flexion of the femorotibial joint.

3. Conjoined tendon (CT) or accessory tendon (AT):

The CT is composed of the tendinous parts of the semitendinosus, biceps femoris, and gracilis muscles.

The semitendinosus muscle originates from the tuber ischii, inserting to the medial aspect of proximal tibia and tuber calcanei. The function of the semitendinosus muscle is extension of the coxofemoral joint, flexion of the femorotibial joint, and extension of the tibiotarsal joint.

The biceps femoris muscle originates from the tuber ischia, inserting at the patella, tibial crest, and tuber calcanei. The function of the biceps femoris muscle is extension of the coxofemoral joint, extension and flexion of the tibiotarsal joint, and extension of the tibiotarsal joint.
The gracilis muscle originates from the pelvic symphysis and inserts on the tuber calcanei. The function of the gracilis muscle is abduction of the coxofemoral joint, femorotibial joint flexion, and tibiotarsal joint extension. The function of the CT has not been described.

### 1.3 Classification of common calcaneal tendon injury:
Injuries of the common calcaneal tendon have been classified into three major types in the veterinary literature based on the location of injury.⁶

1. **Type I**: complete tendon rupture resulting in a plantigrade stance of the affected limb.  
   In subchronic cases, diffuse swelling at the tendon ends may be palpable.⁶
2. **Type II**: slight to moderate flexion of the hock may be noticeable. It is likely partial rupture of the tendons. Type II is further divided into three subtypes.
   a. **Type IIA**: inflammation or oedema may be evident at the musculotendinous junction in acute cases, while swelling will not be palpable in chronic cases.  
      With full extension of the stifle joint, the hock joint can be flexed partially without flexion of the digits.
   b. **Type IIB**: a clear gap may be palpable in acute cases. The paratenon should be palpable between the tendon ends. The flexion of the hock joint is only partially possible without flexion of the digits.
   c. **Type IIC**: GT rupture with intact SDFT. Flexion of the digits when standing will be evident.
3. **Type III**: These are chronic CCT injuries. Affected dogs will have a normal stance and the CCT will be thickened when palpated. Incomplete rupture, microtrauma followed by inflammation, or localized tendinitis could be suspected hence no histopathology was available.⁶
1.4 **Pathogenesis:**

CCT injuries can be acute injuries, as a result of full or partial transection by a sharp object, or chronic injuries as a result of degenerative rupture. Partial tendon rupture (type II) is reported to be the most common form of common calcaneal tendon injuries. In the case of chronic disease, the GT is most commonly affected. In a case series, most cases were acute in onset (67%), and were usually closed injuries (76%). All tendon components were affected in 27% of cases, only the GT was affected in 20% of cases, and the CT and GT were affected in 22%. The osseotendinous junction was the most common site of injury (60%). In chronic type III cases, microtrauma to the CCT due to repeated stress is postulated to be the cause of tendon degeneration.
Figure 3. The anatomy of canine Achilles system. Note the origins and insertion of GT, SDFT, and CT (from Reike, 1982, Comp Cont Educ).
1.5 Common calcaneal tendon repair methods:
It is recommended that acute CCT injuries be repaired surgically as soon as possible after
injury because the area may be contaminated by 4 hours after injury.\textsuperscript{5} Each tendinous
component of the CCT should be repaired individually if possible.\textsuperscript{5} The aim of tendon repair
is to provide a strong repair which is resistant to gap formation at the site of anastomosis and
is able to support the tendon during healing.\textsuperscript{11} The repaired tendon relies on the strength and
holding power of the suture material for first few weeks of healing.\textsuperscript{11} Suturing with specific
suture material and suture patterns with postsurgical tibiotalar joint hyperextension and
immobilization to protect the repair is believed to be important to manage CCT repair.
Various types of suture patterns have been reported: three-loop pulley, Bunnell, and locking
loop patterns. The three-loop pulley pattern is the combination of three continuous horizontal
mattress pattern in three planes about 120 degree (\textbf{Figure 4}).\textsuperscript{12} Monofilament suture material
is preferred because the locking suture patterns are tightened much easier with monofilament
materials without tissue dragging.\textsuperscript{12} Biomechanical analysis of suture patterns have been
done, and the three-loop pulley suture pattern is reported to be stronger and has better
apposition of the tendon ends, minimizing a gap formation, than other suture techniques.\textsuperscript{11,12}
1.6 Tendon healing (duration, gap formation, immobilization, lack of vascularity, sequence of events):

The repaired tendon relies on the strength of the suture material, the suture holding strength, and minimal gap formation for the first few weeks of healing.\textsuperscript{1,11-13} A stronger anastomosis repair allows for early mobilization of the healing tendon, which directly encourages healing, prevents adhesion, and increases the ultimate tensile strength.\textsuperscript{14} Gap formation critically delays the healing process and weakens the repair site.\textsuperscript{11} Gelberman \textit{et al.} demonstrated a gap of more than 3 mm increases the risk of repair failure during the first 6 weeks of recovery.\textsuperscript{15}

Although it may not particularly apply to the canine GT, only 25 to 33\% of tendon strength is necessary to withstand the normal muscle tensile strain.\textsuperscript{1} It was reported that the triceps healing and strength post tenorrhaphy was 56\% at 6 weeks postoperatively.\textsuperscript{1} The tendon healing appeared to strengthen if moderate exercise was introduced as soon as 3 weeks.
postoperatively, and the strength of the healed tendon was 79% of intact tendons after 1 year of the surgery. Therefore, 6 weeks of immobilization was adequate after tenorrhaphy. On the other hand, Woo et al. showed detrimental effects of 6 weeks of immobilization to the ligament tensile strength compared with no immobilization or 3 weeks of immobilization by canine stifle medial collateral ligament study. Early controlled motion and stress to the tendon induces a stronger tensile property. A study with canine digital flexor tendon revealed that gradually increasing passive motion of the repair site between 3 and 12 weeks after repair resulted in significant increase in tensile strength of the tendons, as well as near normal peritendinous vascularity. The hind limb peak vertical force (PVF) in trotting dog has been calculated approximately 65-75 % of its body weight. Based on this data, Moores and others estimated that the possible force the Achilles mechanism would generate was 399N, which will not be able to be tolerated by the fresh tendon repair. The maximum load that canine Achilles tendons repaired with a three loop pulley suture could resist without forming a gap of more than 3mm gap was 173N. Therefore, it is crucial to protect the tendon repair by supplemental support in the postoperative period.

Biomechanical testing revealed that the more distal parts of both the GT and SDFT had 50-70% lower tensile strength than the proximal sections. Moreover, the tensile load of the distal GT was 35% lower than that of the distal SDFT. This study showed that different biomechanical characteristics were present in various areas within the same tendon. A significantly greater elasticity in fibrocartilaginous areas than parallel fibered areas was demonstrated biomechanically. Fibrocartilaginous sections tend to absorb pressure and shearing forces, whereas parallel fibered sections transmit tensile forces effectively because these are stiffer. Poor vascularization at the fibrocartilaginous sections in tendons and might be related to tendon rupture in human. Spontaneous ruptures of the canine GT have been reported at the distal areas or the junction of the attachment to the tuber calcanei, where the
fibrocartilaginous sections had lower vascularity. These relatively and these avascular areas may be involved in the pathogenesis of spontaneous tendon rupture.\textsuperscript{4}

In contrast to the study by Jopp and Reese, Gilbert and others did not find avascular areas in the fibrocartilaginous cap.\textsuperscript{20} They evaluated the vascularity along the common calcaneal tendon in dogs, and the study revealed that the section at the calcaneal insertion had the highest mean vessel count.\textsuperscript{20} The number of vessels gradually decreased towards the mid-body of the tendon, but gradually increased again toward the musculotendinous junction.\textsuperscript{20} According to the study, the macroscopic vascularity of the CCT might be segmental, but it is not clear if microscopic interconnections were present.\textsuperscript{20} Although chronic CCT tendinopathy in the dog tends to be more likely to be close to the calcaneal insertion,\textsuperscript{5,6} the result of these studies revealed that the common site for chronic tendon injury appeared to have a good blood supply and suggested that poor vascularity is less likely to be the predisposing factor in canine chronic tendinopathy.\textsuperscript{20} On the other hand, in a large numbers of human studies, the most common location for the tendon rupture is the mid-body of the tendon accounting for 66\% of all Achilles tendinopathy,\textsuperscript{21} and poor vascularity could be related.\textsuperscript{19} Most of complications after tenorrhaphy were considered to be related to the immobilization methods rather than to the tendon repair methods,\textsuperscript{22} therefore selection of an appropriate immobilization technique is an important part of surgical management of CCT injury.

### 1.7 Immobilization versus consequences of unrestricted motion:

Unrestricted range of motion of the joint can cause catastrophic failure of the tendon repair: gap formation followed by tendon scar and granuloma formation.\textsuperscript{23} Transarticular tibiotarsal immobilization by any method is reported to protect the tendon anastomosis of the CCT after primary repair. Clinically, all reported methods of immobilization appear to work well.
However, restricted movement of the joint does have adverse consequences on the health of the joint and cartilage.\textsuperscript{24,25} Prolonged immobilization of joints has negative effect for the joint, causing joint atrophy, chondromalacia, and decreased range of motion after the immobilization apparatus is removed.

\subsection*{1.8 Modes of immobilization after tendon repair:}
A variety of post-operative immobilization methods have been reported in the veterinary literature after Achilles tendon repair. These include: cranial cast application,\textsuperscript{10} tibiocalcaneal screw,\textsuperscript{5,26,27} tibiocalcaneal screw and cast,\textsuperscript{9} transarticular linear external skeletal fixation (ESF),\textsuperscript{22,28} transarticular circular ESF,\textsuperscript{29} single ring circular fixator\textsuperscript{30} and, more recently, a hinged transarticular ESF have been described for multiple ligamentous injury,\textsuperscript{31} which may be useful for the CCT repair. Most recently, conservative treatment of GT strain with autologous mesenchymal stem cells and a custom orthosis has been reported with successful outcome.\textsuperscript{32} Even though patients clinically recover well postoperatively, there is no clear benefit of any one immobilization method. To date, there is no gold standard for immobilization after CCT injury repair over the duration of treatment.

Each fixation method has potential advantages and disadvantages.

1. The advantages of cast/splint include low cost, ease of application, and, less invasive than other methods. The disadvantages of cast include requirement for frequent changes and bandage-related complications.\textsuperscript{33} Cast- and bandage-related complications occur frequently. Pressure sores, dermatitis, and severe infection are common and can have significant adverse effects. It is also important that the costs for periodical bandage changes may be comparative to costs of other methods.
2. The advantages of tibiocalcaneal screw are: easy to perform and low cost. The
carcaneotibial screw may need adjunctive support, such as a cranial cast in larger patients.
Implant failure has been reported in 8% of cases.9

3. The potential advantages of ESF application are: rigid fixation, better tolerance by
patients, wound is exposed for examination or treatment, easier tendon palpation and
evaluation and early weight bearing which may reduce muscle atrophy.28 Disadvantages
of ESF application are: prolonged surgical time and more implant-related cost.22 ESF
application complications can be catastrophic, including osteomyelitis, iatrogenic
fracture, pin tract drainage and owners may be required to perform daily cleaning
maintenance of the ESF.22 Patient compliance is also an important factor. ESF application
is controversial if all of three components of the CCT are transected (type I lesion),
because this theory ignores the force of SDFT, which would have tension from the digit
extension during normal posture. However, most cases have been treated successfully
using transarticular ESF.22

1.9 Adverse consequences of transarticular immobilization:
Prolonged transarticular immobilization by any method is detrimental for the joint, causing
joint atrophy, chondromalacia, and decreased range of motion after the immobilization
apparatus is removed. One canine study showed that remobilization of the affected joint after
11 weeks of immobilization, immobilization-induced cartilage atrophy was incompletely
restored by remobilization.25 In another study in a sheep model, Bruce et al. compared the
effect of joint immobilization, twice daily passive motion and voluntary motion on articular
cartilage by using hinged transarticular ESF.24 They found that the restoration of articular
cartilage was excellent in the voluntary motion group, while the twice daily passive range of
motion group did not demonstrate statistically significant cartilage repair or range of motion
the joint during the experiment compared to complete immobilization of the joint.24 Extended
immobilization by using ESF generated a significant proteoglycan content of the cartilage, and it was worse than casts, which probably allowed limited movement. Moreover, the cartilage was not restored by one week after ESF removal, although the cartilage was restored in one week for the casted group. Therefore, Behrens et al. suggested the use of transarticular ESF be as short as possible to minimize articular cartilage degeneration, and more optimally allowing 5 to 10 degree of limited joint motion within the ESF should be beneficial. Sivacolundhu et al. recommended 4 weeks of rigid fixation, followed by 3 weeks of soft bandage support to gradually introduce more mechanical load to the tibiotarsal joint and tenorrhapy site.

1.10 Studies with benefits of early controlled range of motion after tendon repair:

In humans with Achilles tendon injuries and repairs, there is a trend to use a hinged ESF for postoperative management of articular ligament damage. Human studies have shown that adequate controlled tension plays a crucial beneficial role in tendon healing. In humans, orthotic boots are used to manage Achilles mechanism injury. Early controlled motion is critical, and studies showed stronger healing of the tendon much earlier in the course of treatment, compared with rigid fixation. In the veterinary literature, the use of a hinged transarticular fixator for multiple ligamentous injury of the stifle and tibiotarsal joints has been described. The hinged transarticular components are commercially available for use in dogs, which make this a feasible approach for CCT injury.

An in vivo rabbit experiment revealed the strain in the CCT was greater than zero Newton (N), and even during quiet standing the tensile force in the CCT was constantly 16 N. Recently the tension of the gastrocnemius tendon during walking was evaluated in conscious dogs, which revealed symmetric (isometric) contraction occurs and the strain was present
even when the tibiotarsal joint was immobilized. This study questioned the current method of immobilization for CCT repair in dogs.
Abstract:

**Objective:** To determine the effects of six types of transarticular immobilization techniques on tibiotarsal joint angles during stimulated weight-bearing.

**Study Design:** Canine *ex vivo* biomechanical study.

**Sample population:** Canine cadaveric pelvic limbs (n=15).

**Methods:** A validation study was conducted to determine before and after transection of the superficial digital flexor tendon in five canine cadaveric limbs without tibiotarsal joint immobilization. Six transarticular tibiotarsal immobilization techniques were tested sequentially in 10 canine cadaveric pelvic limbs. The tibiotarsal joint angles were measured from lateral projection radiographs before and during axial loading of 200N. Mixed linear models were applied to determine the effects of the immobilization techniques on change in tibiotarsal joint angle under loading.

**Results:** There was no change of tibiotarsal joint angle between extended digits and flexed digits under both unloaded and loaded conditions. Change in tibiotarsal joint angles did not differ between any of the immobilization techniques tested here (mean change 1.36 degrees, range 0-5 degrees). The main contributor to variance in angle explained by the final model was associated with the random effect for limb.
**Conclusion:** Changes in tibiotarsal joint angles during single static loading in canine cadaveric limbs for the six immobilization techniques were minimal.

**Clinical significance:** The six techniques appear equally effective at limiting tibiotarsal joint flexion during single axial loading of 200N. Cyclic mechanical testing of these techniques is recommended to support our findings and validate their clinical application.

Elements of this chapter have been published in the Veterinary Surgery journal:

Biomechanical evaluation of 6 transarticular tibiotarsal immobilization methods in canine cadaveric limbs.


DOI: 10.1111/vsu.12923
2.1 Introduction:
Common calcaneal tendon (CCT) injuries occur in dogs as a result of acute, direct, sharp trauma or chronic degenerative injuries. CCT injuries can cause swelling at the affected area and significant functional impairment to the limb, such as hyperflexion of the tibiotarsal joint and a plantigrade stance. The injury can lead to different degrees of lameness due to pain and tibiotarsal joint instability. CCT injuries are classified into types 1, 2a-c or 3 based on chronicity, etiologies, and location of tendon pathology. The indication for surgical intervention depends on the type of injury, nature of injury (acute or chronic onset), closed or open (clean, contaminated, or dirty) and location of injury (muscular or tendinous part). Surgical treatment by tenorrhaphy and temporary post-operative tibiotarsal joint immobilization has been recommended when all three tendon components are ruptured or increased flexion of the tibiotarsal joint is present during weight bearing. Some case reports have described successful outcomes in dogs with partial ruptures treated without tenorrhaphy.

Tendon healing is slow relative to many other tissues due to the relatively poor vascular supply of tendons. Tendons never regain 100% of their pre-injury tensile strength after repair. Temporary immobilization of the tibiotarsal joint in hyperextension is recommended for 3-6 weeks after tendon repair to decrease tendon strain and prevent gap formation during tendon healing. Gap formation can adversely affect the tensile strength and duration of tendon healing. The tendon gap heals with fibrous tissue, which is mechanically inferior to the original tendon structure. Transarticular immobilization, however, can cause significant morbidity of the joint, including articular cartilage atrophy and soft tissue complications. Early controlled mobilization has been advocated in human patients to reduce articular cartilage atrophy and to provide appropriately controlled limited strain to the anastomosis site.
A variety of postoperative tibiotarsal immobilization methods after CCT repair have been described in the veterinary literature including cranial cast application,\textsuperscript{10} calcaneotibial positional screw,\textsuperscript{5} calcaneotibial screw and cast,\textsuperscript{9,38} transarticular linear external skeletal fixation (ESF),\textsuperscript{22,27,28} transarticular circular ESF,\textsuperscript{29} and single circular ring.\textsuperscript{30} Nielsen and Pluhar observed better functional recovery in dogs treated with transarticular ESF compared to cast immobilization, although the difference was not statistically significant.\textsuperscript{22} Most complications after tenorrhaphy are considered to be related to the immobilization technique rather than to the method of tendon repair.\textsuperscript{22}

The authors are not aware of any studies in the veterinary literature that directly compare the ability of different reported transarticular immobilization techniques to limit tibiotarsal joint movement. Canine cadaveric limbs were used in this study as a model of the normal weight bearing pelvic limb to evaluate the ability of six transarticular immobilization techniques to limit change in tibiotarsal joint angle during axial loading. Tibiotarsal joint angles were measured before and during single static axial loading of 200N. We hypothesized that the type II ESF would result in the least change in tibiotarsal joint angle under loading.
2.2 Materials and methods:
This study was approved by the Office for Research Ethics and Integrity at Melbourne Veterinary School, The University of Melbourne (Animal Ethics ID # 14003). Fifteen pelvic limbs were collected from clinically healthy greyhound dogs, weighing between 25kg and 35kg, that were euthanized for reasons unrelated to this project. Limbs were stored at -20°C. Skin was preserved as much as possible to prevent desiccation during the experiment. Limbs were thawed in air to room temperature 24 hours before the experiment. Lateral projection radiographs of the limbs were used to screen for pre-existing orthopaedic disease prior to the experiment.

2.2.1 Specimen preparation:
The stifle joint was rigidly immobilized at 135 degrees, the normal standing angle of the canine stifle joint,39 using a transarticular type II ESF (small-medium SK linear ESF system, IMEX Veterinary Inc., TX). The stifle transarticular type II ESF was constructed with three centrally threaded positive profile 3.2mm shaft diameter transfixation pins (centerface pin IMEX Veterinary Inc., TX) placed parallel to each other in the proximal, middle and distal part of the femur, and three pins placed in the proximal half of the tibia. These transfixation pins were connected to 6mm-diameter titanium and/or carbon fiber connecting rods using small-medium SK clamps (IMEX Veterinary Inc., TX). Another connecting rod was attached using double clamps between the existing two rods to form a triangle-shaped reinforcement of the stifle transarticular ESF construct at both medial and lateral sides of the stifle (Figure 5).
2.2.2 **Validation phase:**

Validation studies were performed in five limbs to demonstrate the effect of the intact CCT on the tibiotarsal joint without immobilization. The stifle joint was fixed at 135 degrees as described above and was placed vertically in a custom jig without any tibiotarsal joint immobilization with normal standing stance of the digits. Lateral view radiographs of the limb were taken using horizontal beam projection ([Figure 2A](#)) before and during axial loading of 200N, and the tibiotarsal joint angles during both conditions were recorded.

A second validation study was performed to evaluate the influence of the superficial digital flexor tendon (SDFT) on tibiotarsal joint flexion ([Figure 2B](#)). Digit flexion produced laxity in the SDFT minimizing the contribution of the SDFT to tibiotarsal joint stability. A padded cast (7.5cm Soffban Natural, 7.5cm Handyband Conforming Bandage, and 7.5cm Delta-Lite Plus, BSN medical Inc., NC) was applied to the metatarsals and distally to the digits with the
digits placed in natural flexion. Lateral view radiographs with horizontal beam were taken again before and during axial loading of 200N, and the tibiotarsal joint angles were recorded. The tibiotarsal joint angles before and during loading were compared between the two validation studies.

2.2.3 Experimental phase:

2.2.3.1 Tibiotarsal joint immobilization techniques:
The tibiotarsal joint of each limb was immobilized sequentially by each of the six different types of immobilization methods in the following order: (1) single circular ring, (2) calcaneotibial screw, (3) calcaneotibial screw plus cranial cast, (4) cranial cast, (5) type IA
linear ESF and (6) type II linear ESF. The sequence of the testing was selected to minimize the potential for mechanical damage to the limb and to optimise the experimental workflow. For single circular ring fixation, an 84mm inner diameter full ring (IMEX Veterinary Inc., TX) was applied to the tibiotarsal joint using a 1.6mm stopper fixation wire (IMEX Veterinary Inc., TX) through the caudal surface of the proximal calcaneus to the distal tibia in the caudodistal-cranioproximal direction. Two divergent 1.6mm smooth fixation wires (IMEX Veterinary Inc., TX) were placed in the distal tibia to stabilize the ring (Figure 7) as described by Norton et al.\textsuperscript{30}

Then, the single ring construct was removed and a hole was drilled using a 2.5mm drill bit (Depuy Synthes Companies, PA) from the caudal aspect of the proximal calcaneus into the distal tibia with the tibiotarsal joint in hyperextension. For calcaneotibial positional screw immobilization, a positional 3.5mm self-tapping cortical screw (DePuy Synthes Companies, PA) was inserted through the drill hole from the caudal surface of the proximal calcaneus to the distal tibia. The calcaneotibial screw plus cranial cast construct was created by adding a cranial cast to the screw construct (Figure 8).
The cranial cast was prepared by bivalving a full cast made using fiberglass casting material (7.5cm Delta-Lite Plus, BSN medical Inc., NC). The cranial cast was applied to the level of the digits, so that the digits were naturally flexed and completely covered by the cast, following orthopaedic padding dressings described by Guerin et al.\textsuperscript{10} To evaluate cranial cast construct without screw, the calcaneotibial screw was removed via a 10mm longitudinal incision at the caudal aspect of the bandage. The Type IA and Type II ESF tibiotarsal fixations were constructed using two centrally threaded positive profile 3.2mm shaft diameter transfixation pins (IMEX Veterinary Inc., TX) engaged in the distal tibia and two centrally threaded positive profile 2.0mm shaft diameter transfixation pins (IMEX Veterinary Inc., TX) inserted in the proximal and mid-metatarsal bones. The proximal pin was inserted to engage all metatarsal bones and the distal pin engaged the third and fourth metatarsal bones.\textsuperscript{28} The fixation pins were connected with single clamps to 6mm diameter carbon fiber connecting rods (IMEX Veterinary Inc., TX) (\textbf{Figure 9}).
2.2.3.2 Evaluation of constructs before and during axial loading:
The limb with the immobilization construct applied was placed in a custom jig with the phalanges extended in a normal standing stance on the experiment floor or, with the digits in flexion for the immobilization methods incorporating a cranial cast. A lateral projection radiograph of the limb, including metatarsals, tibia, and distal femur was taken before loading.

An axial load of 200N was applied to the top of the limb by means of a 20Kg weight, and a second lateral projection radiograph was taken immediately after the load application. The load of 200N was selected for this study based on the following assumptions and calculations. The peak vertical force to the pelvic limb of dogs is reported to be between 35% and 75% of the body weight during walking and trotting, respectively.\textsuperscript{17,40} We assumed the mean body weight of the dogs was 30kg. Based on \textbf{Equation 1}, the calculation resulted in an approximate load of 200N.

\textbf{Figure 9.} A dorsopalmar view photograph of a transarticular type II ESF immobilization technique.
Load required = MBW * PVF * 9.8 m/s²

**Equation 1:** Determination of load applied. MBW: mean body weight, PVF: peak vertical force

The process was repeated with each limb (n=10) for all six of the immobilization methods with radiographs taken before and during loading so that a total of 12 tibiotarsal joint angles were recorded for each limb.

**2.2.3.3 Measurement of the tibiotarsal joint angle:**
The tibiotarsal joint angles were measured from the radiographs using commercially available DICOM viewing software (SYNAPSE PACS v3.1 Fuji Film Holdings Corporation, Tokyo Japan). The tibiotarsal joint angle was measured as the angle between the mechanical axis of the tibia and a line connecting the center of the talus and the center point of the distal diaphysis of the third metatarsal bone. The mechanical axis of the tibia was a line from the midpoint between the medial and lateral intercondylar tuberances to the center of the talus (Figure 10).
Measuring and recording of the joint angle data were performed by a single observer. Each observation was made in triplicate, with the replicates obtained at least 24 hours apart. Each of the triplicate observations was summarized by the arithmetic mean. Intra-observer variability for the angle measurements was assessed using the relative standard deviation of the triplicate measures.

2.2.3.4 Statistical analysis:
Data analysis was conducted in MATLAB 2015 (The Mathworks, Inc., MA). The final data set comprised 120 angle observations (10 observations for each of 6 treatments, before and during loading).

The statistical analysis was conducted via a general linear model, of the form;

\[
Y = \beta X + c + \eta_i + \epsilon
\]
Where ‘Y’ is the response (dependent) variable, X is a vector of predictor (independent) variables, β is a vector of coefficients, c is the y-axis intercept, η_i is the random effect for the i_th subject, and ε is the residual error, which is assumed to be normally distributed with mean zero; N (0, σ^2_ε). The parameters to be estimated from the data are therefore the coefficient values β (effect size), the random effects η (the between-subject variability), the y-axis intercept c, and the standard deviation of the residual error σ^2_ε.

Candidate predictor variables in the models were the presence of loading (LOADING), and the two-way interaction of loading and immobilization methods (LOADING*TREATMENT). Assuming that treatments had no effect on the measured angle in the absence of loading, treatment alone was not considered as a predictor in the models. Limb was included as a random effect. The parameters were estimated by maximum likelihood estimation, using the ‘fitlme’ function in MATLAB.

Candidate predictors were sequentially added and removed to determine the optimum model. The relative quality of the candidate models was assessed using the log-likelihood and the Akaike’s information criterion, histograms and q-q plots of the residuals, and 95% confidence intervals of the parameter estimates.
2.3 Results:
None of the limbs used in the study had radiographic evidence of orthopaedic disease.

2.3.1 Validation phase:
The mean intra-observer variation for each measurement in the tibiotarsal joint angle was 0.8% (range 0-2.5%). In the first validation study, the mean tibiotarsal joint was 127 degrees (range 114-133 degrees) before loading and 101 degrees (range 94-111 degrees) during loading, respectively. In the second validation study, the mean preload tibiotarsal joint angle with digits flexed in the cast was 127 degrees (range 117-135 degrees), and the angle during loading was 102 degrees (range 94-113 degrees). The mean change in tibiotarsal joint angle was 26 degrees with digit extension (normal stance) and 25 degrees with digit flexion (cast). There was little change of tibiotarsal joint angle between extended digits and flexed digits under both unloaded and loaded conditions.

2.3.2 Evaluation of six immobilization techniques:
The mean relative standard deviation across measurements at preloading was 0.8% (range 0-2.6%), and at loading was 0.9% (range 0-2.9%). All immobilization techniques evaluated in this study effectively limited movement of the tibiotarsal joint during static loading of 200N. There was no significant difference in the change in tibiotarsal joint angles between all immobilization techniques. The final model did not provide evidence that the ESF type II was superior to any other immobilization method. Therefore, our hypothesis was rejected. The results are summarized in Table 1.
### Table 1. Statistical comparison of immobilization techniques.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate (degrees)</th>
<th>Lower CI (degrees)</th>
<th>Upper CI (degrees)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RING (baseline effect)</td>
<td>163.13 (0)</td>
<td>159 (-4.13)</td>
<td>167.26 (4.13)</td>
<td>&lt;10^-10</td>
</tr>
<tr>
<td>SCREW</td>
<td>3.8</td>
<td>0.15323</td>
<td>7.4468</td>
<td>0.041266</td>
</tr>
<tr>
<td>SCREW+CAST</td>
<td>2.4667</td>
<td>-1.1801</td>
<td>6.1134</td>
<td>0.18291</td>
</tr>
<tr>
<td>CAST</td>
<td>0.73333</td>
<td>-2.9134</td>
<td>4.3801</td>
<td>0.69109</td>
</tr>
<tr>
<td>ESF TYPE I</td>
<td>1.5</td>
<td>-2.1468</td>
<td>5.1468</td>
<td>0.41684</td>
</tr>
<tr>
<td>ESF TYPE II</td>
<td>2.9</td>
<td>-0.74677</td>
<td>6.5468</td>
<td>0.11794</td>
</tr>
<tr>
<td>1:ID</td>
<td>6.3742*</td>
<td>4.0501</td>
<td>10.032</td>
<td></td>
</tr>
<tr>
<td>ERROR</td>
<td>4.1159†</td>
<td>3.6065</td>
<td>4.6974</td>
<td></td>
</tr>
</tbody>
</table>

RING (Single ring) is the baseline effect with estimate (effect size) of zero. ERROR is the model’s residual error. Lower CI and upper CI are the lower and upper bounds of the 95% confidence interval for the parameter estimates, respectively. 1:ID is the random effect for limb. The p-value is the probability of the null hypothesis, a coefficient value of zero for the parameter. * estimate is the standard deviation of the intercept for the random effect. † estimate is the standard deviation of the residual error.

The single ring construct, the baseline effect in the model, had the greatest change in tibiotarsal joint angle during loading. The calcaneotibial screw construct had a positive effect ($\beta = 3.8$) and was the only significantly different technique (95% CI: 0.153-7.45) compared...
to the single ring construct. However, the magnitude of the difference was small (Figure 11). Distal displacement of the stifle during axial loading was observed in the single ring, calcaneal screw, and ESF immobilization techniques. No change in stifle angle was observed during loading.

**Figure 11.** Box-plot of the angle data; the data points are the mean of triplicate observations. For each treatment, the left box is the pre-loading angle (n = 10), and the right box is the post-loading angle (n = 10). An apparent outlier is marked as an open circle. The mean change in angle for the ring, screw, screw and cast, ESF type I, and ESF type II were 3.67, 1.47, 1.17, 1.9, and 1.23 degrees, respectively.
2.4 Discussion:

All of the immobilization techniques tested were similarly effective at limiting tibiotarsal joint movement during single static loading of 200N.

The tibiotarsal joint angles across immobilization methods varied minimally, and intra-observer variability was small (0.8% or 1.36 degrees). Therefore, immobilization techniques and intra-observer variability were not considered as contributing factors for the variance in the data. The magnitude of the within-limb variability (STD = 6.37 degrees) and the error variability (STD = 4.12 degrees) both exceeded the effect size of all the immobilization methods. The effect of immobilization methods very weakly explained the observed data variance in the absence of the limb-level random effect ($R^2 = 0.0147$), but the model with random effect was highly explanatory ($R^2 = 0.720$), demonstrating relatively large variability between limbs regardless of immobilization methods. This observation may be clinically important as a contributor to between-patient response to the tibiotarsal immobilization.

The single ring construct had the largest change in the tibiotarsal joint angle during loading and greatest variability between limbs. However, the magnitude of the difference was very small. The final model indicated that the effects of the immobilization methods under loading were positive compared to the single ring technique (Table 1). This indicates that the single ring technique was associated with the largest change in the tibiotarsal joint angle during loading. Only the effect of the screw construct was significant ($p = 0.04$). It is reasonable to assume that greater joint movement during loading may be associated with adverse effects on tendon healing and a higher chance of implant failure. The small effect sizes observed in this study suggest that the difference between immobilization methods may be of limited clinical significance. Further evaluations, such as cyclic loading, would be required to determine if the observed difference in effect for the single ring technique and screw construct is clinically relevant.
The tibiotarsal joint angle during loading was not different between the first and second validation study (101 and 102 degrees, respectively). The validation studies demonstrated that the intact CCT would not be subject to strain with the immobilized tibiotarsal joint in hyperextension (>150 degrees). For this reason, transection of the CCT was not performed for the subsequent experiments. The second validation study showed that the SDFT did not have an effect on the change in the tibiotarsal joint angle before and during loading with either the digits flexed in the cast or with hyperextension of the metatarsophalangeal joints (normal standing stance).

The sequence of testing was selected to minimize the potential for mechanical damage to the limb and to optimise the experimental workflow. Each radiograph was assessed for fracture or failure of the construct. There was no radiographic or palpable construct failure before and during loading.

During loading, the stifle joint angle did not visually change, but the location of the stifle joint was transposed distally during axial loading in the single ring, calcaneotibial screw, and ESF immobilized limbs. This displacement was due to extension of the metatarsophalangeal joint and compression of the footpad to the floor, absorbing the applied load (Figure 12). This distal stifle displacement was not observed in the cast only and screw plus cast immobilization methods.
The single ring construct had the greatest variance in tibiotarsal joint angle change during loading. In the single circular ring fixation, hyperextension of the tibiotarsal joint is maintained by the small stopper on the fixation wire at the caudal aspect of the calcaneus and tensioning of the wire on the ring. The ring is secured to the distal tibia with two divergent smooth fixation wires. Therefore, all the force in the tibiotarsal joint concentrates at the stopper part of the fixation wire at the caudal surface of the calcaneus. The balance of adequate tension and movement of the calcaneus can be difficult to adjust. Elongation of the stopper wire and slippage between the wires, ring and fixation bolts could contribute to less stability compared to other immobilization methods.

We hypothesized that the type II ESF immobilization technique would be the stiffest construct and therefore provide the greatest resistance to change in tibiotarsal joint angle under loading. However, the results did not provide evidence that the ESF type II was superior to the other immobilization methods. The difference between the type IA and the type II ESF was not significant. Because the diameter of the metatarsal bones are much smaller compared to the tibia, smaller diameter transfixation pins need to be used in the metatarsal bones. The load of 200N caused deformation of the 2.0mm diameter transfixation pins in the metatarsals that resulted in a changed tibiotarsal joint angle despite no change in

**Figure 12.**
A: A photograph of a distal limb without loading. Note type Ia ESF was used in this photograph.
B: A photograph of a distal limb during loading. Note the angle of the metatarsophalangeal joint is narrower and the paw is more compressed into the floor, compared to the limb shown in Figure 12A.
the angle of the ESF construct. The measurement between the connecting clamps did not change from unloaded and loaded radiographs indicating that the stiffness of the connecting bars and clamps was appropriate. A slight deformity of the most distal transfixation pin was observed by direct visualization during loading, but the dorsopalmar projection radiographic measurement of the change in length between transfixation pins was less than 0.1mm (Figure 9). Although this may not be a significant problem in the clinical scenario, we suspect that the weakness caused by thinner pins could increase the risk of implant failure in cyclic loading due to micromotion. It is difficult to improve the construct stiffness since smaller pin insertions and limited numbers of pins dictate the stiffness of the linear ESF. Increasing the numbers of pins in the metatarsals may increase the risk of fracture due to small metatarsal bone diameter. A circular or hybrid ESF fixation using tensioned fine wires in the metatarsals may provide more effective metatarsal bone purchase without increasing the risk of metatarsal fractures.29
There are several limitations to this study. The results of this study must be interpreted cautiously due to the use of cadaver limbs and single static loading testing and should not be used to make clinical recommendations.

The reported normal standing angle of the tibiotarsal joint in dogs is 140 degrees. The standing angle of the tibiotarsal joint without loading in limbs used in this study without tibiotarsal joint stabilization was approximately 130 degrees. Spontaneous isometric contractions of muscles maintain normal posture in live standing animals. The difference of 10 degrees between reported normal and cadaver limbs may be explained by muscle relaxation and lack of isometric contraction in the cadaveric limbs. The contribution of active or isometric muscle contraction to the stability of the tibiotarsal joint is ignored in cadaveric

**Figure 13.**

A: A closer photographic view of the limb using type II ESF before loading.

B: A dorsopalmar view radiograph of a limb shown in Figure 13A.

C: A close-up dorsopalmar view photograph of the limb using type II ESF during loading. Note no visual changes were detected during testing.

D: A dorsopalmar radiograph of the limb during loading shown in Figure 13B. Note no radiographic changes were detected.
studies. The pelvic limb was disarticulated at the coxofemoral joint, and therefore some muscles including the semitendinosus and quadriceps muscle group had to be separated from their origin. This does not fully replicate the in vivo clinical situation, such as the contribution and effect of muscle contraction on tibiotarsal joint stability. However, this study was designed to test the ability of various immobilization techniques to limit changes in tibiotarsal joint angle in limbs under static loading conditions.

The failure to detect differences between immobilization methods may result from the sample size, but the estimated effect sizes in this study suggest an absence of clinically meaningful differences between immobilization methods other than single ring construct. The change in angles was assessed by a single observer with angle measurement performed on three occasions on different days. The study could not be blinded because implants were visible at the tibiotarsal joint and easy to recognize during assessment. The variability was minimal, and the repeatability was excellent. The variability of the angles was minimal (0.8-0.9%), which was equivalent to or even better than the other study for comparison of goniometry and radiographic measurement. A load of 200N was selected for the experiment, based on calculations by Moores et al. in which peak vertical force of 399N for a 30Kg dog at a trot was estimated. In our study samples, the body weight varied between 25 and 35Kg, and a load of 200N would represent approximately 57 to 80% of individual body weight. 200N would be well above the peak vertical force during walking. Because the limbs were supplied individually separated from dogs, a particular limb of the body weight of the dog was unknown. To standardize the data, we used the tibial mechanical axis length as a variance, but it did not demonstrate significant correlation with the results. Ideally, cyclic fatigue testing with lower loading would represent a more clinically relevant evaluation to compare tibiotarsal joint movement and implant stability with different immobilization techniques. However, this was not financially or
technically feasible for this study. Single static loading with 200N was selected as an appropriate model to evaluate and compare the immobilization methods.

In conclusion, the six different immobilization techniques evaluated in this study all provided similar immobilization of the tibiotarsal joint during single static loading of 200N. Mechanical testing using repetitive cyclic loading is recommended. Selection of a tibiotarsal joint immobilization technique after CCT repair should be based on consideration of patient, client, and environmental factors, surgeon preference and the reported advantages and disadvantages of each immobilization technique.
3 The Effect of the Femorotibial and Tibiotarsal Joint Range of Motion on the Gastrocnemius Muscle-Tendon Working Length in the Canine Cadaveric Limb

Abstract:

Objective: To determine the biomechanical characteristics of the gastrocnemius muscle–tendon unit (GMTU) in the canine cadaveric limb.

Study Design: Ex vivo kinematic study.

Animals: Canine cadaveric pelvic limbs (n=11).

Procedures: Dissection of a cadaveric pelvic limb was performed to identify anatomical origin and insertion of the GMTU for the radiographic landmark determination. Radiographic reference points of the femorotibial joint (FTJ) and tibiotarsal joint (TTJ) were identified by lateral view radiographs in eight limbs. A series of lateral radiographs were evaluated to measure the linear length of the GMTU at any combinations of the FTJ (90, 105, 120, 135, and 150 degrees) and TTJ (110, 125, 140, 155, and 170 degrees). Gap formation at the GMTU anastomosis site using a three-loop pulley suture was evaluated in 10 limbs in various angle combinations. Mathematical calculation was compared to the ex vivo model to predict the working length of the GMTU.

Results: A nearly linear change in the GMTU was observed within the physiological range of motion (ROM) of the FTJ and TTJ. Gap formation was detected when the FTJ >135 degrees and the TTJ <125 degrees. There was no difference in gap formation between three groups (location of anastomosis or intact superficial digital flexor tendon).

Conclusions and Clinical Relevance: Thirty degrees of free ROM of the TTJ (140-170 degrees) may be allowed immediately postoperative period without increased risk of
tenorrhaphy failure. No limit of the TTJ ROM is possible if synchronized movement of the FTJ is simultaneously provided.

Components of this Chapter have been prepared and accepted for podium presentation at American College of Veterinary Surgeons (ACVS) Surgery Summit in October 2018, and submitted for peer-review publication.
3.1 Introduction:
Common calcaneal tendon (CCT) injuries occur in dogs as a result of acute, direct, sharp trauma or chronic degenerative injuries.\(^3,^8\) CCT injuries can cause clinically significant functional impairment to the pelvic limb, such as hyperflexion of the tibiotalar joint (TTJ), swelling at the affected area, and plantigrade stance, causing a variable degrees of lameness due to pain and instability at the TTJ.\(^5,^8\) A surgical treatment has been recommended when all three tendon components are ruptured or increased flexion of the TTJ is present during weight bearing.\(^9,^{10,22,27}\) Successful outcomes in dogs have been reported with more conservative approach for partial CCT ruptures without tenorrhaphy.\(^32,^{38}\)

Tendon healing is slow due to relatively poor vascular supply of the tendon.\(^4\) Tendons do not recover 100\% of their pre-injury tensile strength after repair.\(^1,^{13}\) Because the gap will heal with mechanically inferior fibrous tissue, gap formation can adversely affect the tensile strength and duration of healing of the tendon.\(^11,^{15}\) Therefore, temporary immobilization of the TTJ in extension is recommended for 3-8 weeks after tendon repair to reduce strain on the tendon and prevent gap formation during tendon healing in the current veterinary practice.\(^5,^{10,27}\)

One of the most important factors affecting outcome of CCT repair is the postoperative management. Transarticular immobilization of the TTJ produces significant morbidity of the joint, such as joint cartilage atrophy and soft tissue complications.\(^24,^{25}\) The tensile strength and duration of the healing of the tendon may be affected due to lack of strain.\(^35\) Early controlled mobilization of the joint has been advocated in human patients to reduce articular cartilage atrophy and to provide appropriately controlled limited strain to the anastomosis site.\(^35\)
The medial and lateral heads of the gastrocnemius muscle-tendon unit (GMTU) originate from a wide surface area between the medial and lateral fabellae and supracondylar tuberosities, respectively. The GMTU terminates onto the lateral side of the proximal surface of the most proximal part of the tuber calcanei. The function of the GMTU is flexion of the femorotibial joint (FTJ) and extension of the TTJ. Since the GMTU spans the FTJ, the length of the GMTU will be affected by not only the range of motion (ROM) of the TTJ, but also the ROM of the FTJ.

Several methods of measuring GMTU length have been described in the human literature. However, there are no reports in the veterinary literature in regard to strain of the GMTU relative to the FTJ and TTJ ROM. The aim of this study was to evaluate the kinematics of the FTJ and TTJ, and evaluate the change in length of the GMTU at the physiologic ROM of the FTJ and TTJ in canine cadaveric limbs. The hypothesis was that some combination degrees of freedom (ROM of the FTJ and/or TTJ) would exist without causing significant increase in the working length of the GMTU.
3.2 Materials and Methods:

The study was approved by the Office for Research Ethics and Integrity, at the University of Melbourne (Animal Ethics ID # 14003). Fifteen pelvic limbs were collected from clinically healthy greyhound dogs weighing between 25kg and 35kg, that were euthanized for reasons unrelated to this project. Limbs were stored at -20°C. Limbs were thawed in air to room temperature 24 hours before the experiment. Lateral projection radiographs were used to screen for pre-existing orthopaedic disease in the limbs prior to the experiment.

3.2.1 Anatomical observation and determination of the measuring points:

One cadaveric pelvic limb was dissected to observe the anatomical origin and insertion of the GMTU. The medial fabella, supracondylar tuberosity, and the origin of the medial gastrocnemius muscle were identified. The superficial digital flexor tendon (SDFT) was dislocated from the calcaneus medially by incising the lateral retinaculum, and the combined tendon and the gastrocnemius tendon were directly visualised and transected at the calcaneal insertion to determine the definitive insertion point.

3.2.2 Specimen preparation and setting:

The majority of the skin, musculatures and tendons were removed from the femur, tibia and metatarsals, leaving the peri-articular and intra-articular structures of the FTJ and TTJ, SDFT, GMTU and patellar ligament similar to the experimental model described by Pozzi et al. Two holes were created in the proximal and distal diaphysis of the tibia, and the tibia was secured onto a custom-made jig panel using two bolts and nuts through the holes, so that the limb to be parallel to the floor (Figure 14). The femur and metatarsus were stabilized to the jig panel according to predetermined angle combinations by tightening of two nuts on bolts through the semicircular slits, respectively. The specimen surface was kept moist during the preparation and experiment by spraying with saline solution.
3.2.3 Combination of the FTJ and TTJ angles:

First, the FTJ was immobilized at 90 degrees. The lateral projection radiographs were taken at the angle of the TTJ with 15 degrees increments (170, 155, 140, 125, and 110 degrees). Then, the procedure was repeated at the angle of the FTJ with 15 degrees increments (90, 105, 120, 135, and 150 degrees). A plastic goniometer was used to measure the FTJ and TTJ angles. The series of radiographs were evaluated for both the FTJ and TTJ to ensure that the determined joint angle was within +/- 5 degrees of aimed angle. The GMTU was not forced to stretch. The angle combination was continued until the GMTU elongation was possible only by gentle traction and the limb was maintained in the desirable angle. If an angle combination could not be maintained due to moderate tension to the GMTU, the experiment was aborted and moved to other angle combination.
3.2.4 Determination of the gastrocnemius muscle-tendon unit working length:
The origin and insertion of the GMTU were identified and a straight line was drawn, and the working length of the GMTU was measured from the lateral radiographs using a commercially available DICOM viewing software (SYNAPSE PACS v3.1 Fuji Film Holdings Corporation, Tokyo Japan).

At first, the origin and insertion of the GMTU was anatomically identified during dissection of a canine cadaveric pelvic limb. The distance between the supracondylar tuberosity and the fabella was ignored in this study to simplify the experiment. The mechanical axis of the GMTU coursed near parallel along the tendon part of the GMTU, which was found to locate between at the most caudal surface of the fabella and at the mid point of the proximal surface of the tuber calcanei. The length of the straight part of the GMTU was measured at each combination of the FTJ and TTJ angles. The femoral reference point for the FTJ was determined by best fitting circle applied along the caudal surface of the femoral condyles as described by O’Brien et al. The reference point of the TTJ was similarly determined by a best-fit circle applied to the trochlea of the talus. The talar reference point is the center of the talus, which is the center of rotation (CR) of the TTJ.

The reference point of the origin and insertion of the GMTU, femoral reference point, and tarsal CR were determined and the working length of the GMTU (G), inter-joint axis of the tibia (T), femorofabellar length (FFL), talocalcaneal length (TCL) were measured (in mm) for each combination of the FTJ and the TTJ angles with 15 degrees increment (Figure 15).
After determination of the trapezium formed by G, T, FFL, and TCL, the following four angles were measured (in degrees): femoro-fabellar angle (FFa), fabello-gastrocnemius angle (FGa), talo-calcaneal angle (TCa), and calcaneo-gastrocnemius angle (CGa) (Figure 16). The reading was performed by a single observer (TS).

Figure 15. Measurement of the length of T, FFL, TCL and GMTU in a sample on the jig. In this sample, FFT was 135 degrees and TTJ was 170 degrees.
3.2.5 *Gap measurement during various combinations of the FTJ and TTJ angles:*

After the kinematic study, all components of the CCT were transected and tenorrhaphy was performed only for the gastrocnemius tendon in each limb tested. In the first four limbs, approximately 2cm proximal to the insertion point of the GMTU was transected, while, the insertion of the GMTU at the calcaneus was transected in the other four limbs. Standard three-loop pulley suture for the first four limbs and a modified three-loop pulley suture were placed in the other four limbs to achieve apposition of the anastomosis site using 2-0 nonabsorbable, monofilament polypropylene (Ethicon™, Johnson and Johnson Medical, NSW, Australia), respectively, described by Berg and Egger¹² and Moores *et al.*¹¹,¹⁸ Another two limbs were prepared to evaluate the effect of the SDFT. These two limbs were prepared described above, but the SDFT was left in situ with the combined tendon transected. The transected GMTU 2cm proximal to the insertion was anastomosed using a standard three-loop pulley suture using the same material as the other limbs. The limb was stabilized onto
the jig panel, and the anastomosis site was assessed for gap formation in various angle combinations of the FTJ and TTJ. First, the FTJ was fixed at 90 degrees, and the TTJ angle was changed from 170 to 110 degrees with 15 degrees increment. Then the procedure was repeated with the FTJ angle increased by 15 degrees increment until gap formation (> 1mm) is detected. During the experiment, the gap was monitored by a ruler along the GMTU (Figure 22).

3.2.6 Statistical analysis:
Data analysis was conducted using the linear mixed model in MATLAB 2015 (The Mathworks, Inc., MA). A mathematical calculation was performed and a mathematical formula was created to predict the behaviour of the GMTU.
3.3 Results:
None of the limbs used in the study had radiographic evidence of orthopaedic disease.

3.3.1 Anatomical observation and radiographic landmark determination:
The origin of the medial GMTU was at a wide surface area between the medial fabella and the supracondylar tuberosity of the femur (Figure 17). The GMTU origin was coming out from the distal femur with the fibers more or less perpendicular to the femoral cortex, and at the fabella. The direction of the GMTU fibers was bent at the fabella, and directed distally toward the proximal calcaneus. The insertion of the GMTU terminated to the lateral two thirds of the caudal half of the proximal surface of the tuber calcanei (Figure 18). Therefore, the mechanical axis of the GMTU is non-linear but curved proximally.
3.3.2 The gastrocnemius muscle-tendon unit working length:

A proportional change in the GMTU working length was observed within the physiological
ROM of the FTJ and TTJ. The data was summarized in Table 3. Combinations that could not
maintain the angles was not recorded. Table 3 combined the data from 3.2.2 and 3.2.3. For
example, the combination of TTJ 120 degrees and TTJ 110 degrees could not demonstrate the
GMTU length. However, no gap formation was observed in the combination. This is marked
as No Gap in blue letter without numbers.

The linear mixed model demonstrated that calcaneal angle was a negative function of tarsal
angle ($\beta = -0.82$), with a small degree of inter-individual variability in calcaneal angle (SD
1.74°), that was smaller than the magnitude of the residual error (SD 3.03°). The coefficient
of determination of the model with fixed and random effects was very high (adjusted R² =
0.9601). Removal of the random effect had minimal effect on the predictive quality (adjusted
R²). Across all subjects and angle combinations, the sum of the calcaneal angle and tarsal
angle was mean 213 degrees (SD 4.82°; RSD 2.26%).

The model demonstrated a significant ($p < 10^{-8}$) effect of femoral angle (FFa) on the
interarticular axis of the tibia (T) ($\beta = 0.082$). This model included inter-individual variability
in T, which was large (SD = 22.22mm) compared to the residual error variability (SD =
2.47mm). The effect of FFa on T was small, but this model was supported by the AIC as
superior to the random-effect only model. The coefficient of determination of the model with
random effect only was very high (adjusted R² = 0.989). A marginal degree of the total
variance was explained by the effect of FFa (adjusted R² = 0.986).

The femoral angle was associated ($\beta = 0.729$) significantly with the stifle angle (95% CI =
0.699-0.760). There was a small degree of inter-individual variability in femoral angle
(2.60°), which was smaller than the magnitude of the residual error (3.74°). The femoral
angle was predicted closely by the fixed and random effect model for stifle angle (adjusted R2 = 0.946). Predictive quality was slightly worse for the fixed effect only model (adjusted R2 = 0.918).

The minimum parameters required for determination of the predicted gastrocnemius length (G) were the T, the FFa, FFL, TCa, and TCL. Together, these parameters describe three sides and two adjacent internal angles of an irregular quadrilateral where the predicted gastrocnemius length is the unknown fourth side. The predicted G is a deterministic result from the mathematical model. Overall the goodness-of-fit diagnostics indicated that the gastrocnemius length predicted by the combination of the parameters was highly accurate by comparison to the measured gastrocnemius length. Root mean squared error (RMSE) for the gastrocnemius length was 4.65mm. The RMSE is comparable to the estimated intra-observer variance for the gastrocnemius length.

The change in working length of the GMTU for each FTJ (90-150 degrees) and TTJ (110-170 degrees) angle combinations was compared to mathematical calculation using a formula, shown in Figure 19 and Figure 20. Based on the cadaveric study, mathematical formula was created (Figure 21 and Equation 1).
Figure 19. A: A mathematical model developed from Figure 19B.

Figure 20. A graph showing the correlation between the raw data and mathematical calculation for GMTU length of a limb. Note the dots are aligned on a straight line. The line represents the line of identity (y = x), and the circles represent actual raw data.
The calculation and reflected the raw data, and the length of the GMTU \((G)\) could be predicted by using the formula.

\[
Determine \ G, \text{where the joint angles (FFa, TCa), and the inter - joint distance (T), are known.}
\]

- \( Fa = S1 + S2 \)
- \( H = \sqrt{TC^2 + T^2 - 2TC \times T \times \cos(TCa)} \)
- \( S2 = \arccos(T^2 - TC^2 + H^2 / 2TH) \)
- \( G = \sqrt{FF^2 + H^2 - 2FF \times H \times \cos(S1)} \)
3.3.3 *Gap measurement during various combinations of the FTJ and TTJ angles:*

No gap formation developed during FTJ angles between 90 and 120 degrees regardless of the TTJ angles in cadaveric limbs using standard or modified three-loop pulley suture. The result of gap formation in various angle combinations was summarized in Table 2. The relationship between the GMTU working length change in percentage (%) and gap formation was summarized in Table 3. Gap formation and the change in GMTU working length when the FTJ at 135 degrees with the TTJ at 125 degrees, 1mm gap formation was observed initially, subsequently enlarged to 3mm when the limb was left as is for several seconds (Figure 22).

![Figure 22. A demonstrative photograph of gap formation during testing.](image)

For assessment of gap formation, five limbs were used for FTJ 135 degrees, and another five limbs were used for assessing FTJ 150 degrees. When the FTJ was 90-125 degrees, no gaps were formed (n=10). When the FTJ was 135 degrees, a gap formed with the TTJ at 125 degrees (n=5). The other five limbs were used to assess for FTJ 150 degrees. When the FTJ was 150 degrees, the gap formed with a TTJ at 140 degrees (n=5). There was no difference in angle combination for gap formation between samples in which proximal (tendon-to-tendon) anastomosis or at the insertion to calcaneus (tendon-to-bone) anastomosis (n=5 each). For
two limbs with intact SDFT, the outcome was not different from the other four limbs. A 3D plots by simulation from the formula was generated (Figure 23). X, Y, and Z axes represent GMTU length, TTJ angle, and FTJ angle, respectively. The ROM of the FTJ and TTJ of the normal stance phase of healthy large breed dogs was indicated by blue lines. The risk of gap formation was indicated by red lines.
Table 2. Gap formation and the FTJ and TTJ angle combinations in 10 pelvic limbs.

<table>
<thead>
<tr>
<th>FTJ angle (degrees)</th>
<th>150</th>
<th>135</th>
<th>120</th>
<th>105</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>N/E (Gap)</td>
<td>N/E (Gap)</td>
<td>No Gap (N=10)</td>
<td>No Gap (N=10)</td>
<td>No Gap (N=10)</td>
</tr>
<tr>
<td>125</td>
<td>N/E (Gap)</td>
<td>Gap (N=5)</td>
<td>No Gap (N=10)</td>
<td>No Gap (N=10)</td>
<td>No Gap (N=10)</td>
</tr>
<tr>
<td>140</td>
<td>Gap (N=5)</td>
<td>No Gap (N=10)</td>
<td>No Gap (N=10)</td>
<td>No Gap (N=10)</td>
<td>No Gap (N=10)</td>
</tr>
<tr>
<td>155</td>
<td>No Gap (N=5)</td>
<td>No Gap (N=10)</td>
<td>No Gap (N=10)</td>
<td>No Gap (N=10)</td>
<td>No Gap (N=10)</td>
</tr>
<tr>
<td>170</td>
<td>No Gap (N=5)</td>
<td>No Gap (N=10)</td>
<td>No Gap (N=10)</td>
<td>No Gap (N=10)</td>
<td>No Gap (N=10)</td>
</tr>
</tbody>
</table>

The result was the same for 10 limbs

- 5 limbs with standard three-loop-pulley (one limb with intact SDFT)
- 5 limbs with modified three-loop-pulley (one limb with intact SDFT)

N/E: Not Examined due to failure at FTJ 135 degrees and TTJ 125 degrees

(Gap): likely gap formation develops, although the combination was not examined due to failure at combination (FTJ 135 degrees - TTJ 125 degrees and FTJ 150 degrees - TTJ 140 degrees)

Gap: Gap formation was confirmed
### Table 3. The GMTU working length changes (%) during ROM of FTJ and TTJ (N=10).

<table>
<thead>
<tr>
<th>FTJ angle (degrees)</th>
<th>150</th>
<th>135</th>
<th>120</th>
<th>105</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>Gap</td>
<td>Gap</td>
<td>No Gap</td>
<td>No Gap</td>
<td>12.8</td>
</tr>
<tr>
<td>125</td>
<td>Gap</td>
<td>Gap</td>
<td>No Gap</td>
<td></td>
<td>11.6</td>
</tr>
<tr>
<td>140</td>
<td>Gap</td>
<td>10.6</td>
<td>9.7</td>
<td>8.1</td>
<td>6.8</td>
</tr>
<tr>
<td>155</td>
<td>9.3</td>
<td>7.8</td>
<td>5.8</td>
<td>3.9</td>
<td>2.5</td>
</tr>
<tr>
<td>170</td>
<td>7.3</td>
<td>4.5</td>
<td>3.8</td>
<td>1.8</td>
<td>0</td>
</tr>
</tbody>
</table>

Blue numbers: Gap formation likely does not develops. Note 0% when the FTJ at 90 degrees and TTJ at 170 degrees.

Red numbers: Gap formation likely develops.

Numbers: GMTU working length with intact CCT (limitation by the tension)

No numbers: no measurement was possible during GMTU length measurement

Gap: gap formation confirmed by testing

No Gap: No gap was detected in given angle combinations but no date was recorded because the GMTU working length could not be measured in the first study (section 3.3.2) due to moderate tension.
Figure 23. 3D plots by simulation from the formula. X axis represents GMTU length, Y axis for TTJ angle, and Z axis is FTJ angle. The area surrounded by the blue line (---) indicates the combination of FTJ and TTJ angle associated with stance phase (FTJ ROM 120-140 degrees and TTJ ROM 130-140 degrees). The area surrounded by the red line (---) indicates the combination of FTJ and TTJ angle associated with the risk of gap formation. The cross-area of the red and blue lines is suspected as the risk zone of gap formation during stance phase.
3.4 Discussion:
In this study, the simplified working length of the GMTU was evaluated in various combination of the FTJ and TTJ angles. It is impossible to specify a definitive point of origin and insertion of the GMTU as it has a wide base origin at the distal femur and wide insertion to the proximal calcaneus. The effect of the SDFT in regard to protective effect of the GMTU was not detected in this study (both Chapter 2 and 3). Based on these results, free ROM of the TTJ between 140 and 170 degrees may not be a risk of gap formation during stance phase. Therefore, our hypothesis was accepted. The risk of gap formation during stance phase would occur when the TTJ angle is <135 degrees. This is also supported from two clinical reports that a free ROM of the TTJ of approximately 30 degrees (range 140-170 degrees) appears to be safe if patients with postoperative confinement is appropriate.28,49

The calculation of the entire GMTU is complicated due to its proximal curved nature of the structure with broad attachment from the supracondylar tuberosity and fabellae. MRI-based calculation and computer simulated anatomic model are difficult and the results were different each other.44 It is very important to know the entire length of the GMTU in human orthopaedics because they use the data for surgical decision-making and determining outcome of GMTU lengthening procedure in certain medical conditions.44 However, our purpose was to determine the absolute working length of the GMTU for determining the safe ROM of the FTJ and TTJ. This was the reason why the length between the supracondylar tuberosity and the fabella was ignored in this study. The course of the fabellae was visible, and the pathway of the origin of the GMTU could be followed in the series of ROM of the FTJ and TTJ in one lateral projection radiographic image by multiple radiographic exposures of the pelvic limb (Figure 24). The blue circles are the point of origin of the GMTU working length. The red circles are the real point that the original blue circle located at the FTJ flexion at 90 degrees. When the FTJ is gradually extended, the distance between the blue and red
circles within the same fabella increases. Moreover, the location of the femoral point moves, and the distance increases (▶). A few mm of difference between flexion and extension will be easily develop depending on how the length is measured. To simplify the complexity of the CCT and FTJ, a straight line of the GMTU axis was obtained from lateral projection radiographs using a custom-made jig panel. Rao et al. compared estimates of GMTU length obtained by straight-line model (similar to our method) and MRI-based segmented model in children during simulated pathological gait to change the GMTU length.43 They found the length was affected by the method and the GMTU length tended to be lower with the straight-line model compared to the segmented model.43 It makes sense as the straight-line model does not consider the origin of the GMTU which increase in significant curvature, and straight-line model does not consider the part, particularly when the FTJ extended, while the TTJ is flexed. Even in human, there is no gold standard technique to assess in vivo GTMU length during activities.43

Yuen et al. compared three methods of measuring the GMTU in human during normal gait.44 The GMTU length change was 9.7% by the cadaveric data, 10.6% by computer simulated anatomic modeling method, and 7.2% by the MRI method.44 Our mean maximum change in the GMTU was 12.8%, but it cannot be compared to different species and different method applied. Moreover, the strain (zero percent) was set at hyperextension of the TTJ (FTJ 90 degrees and TTJ 170 degrees) and CCT was flaccid, and the “slack” was not eliminated. The Transarticular ESF immobilized in two different TTJ angles was used for six dogs after CCT tenorrhaphy: one for normal standing angle approximately 135 degrees and the other hyperextension approximately 160 degrees), and the clinical outcome of the both constructs was not different.28 De Haan et al. reported four successful transarticular immobilization at approximately 150 degrees.49 Given these clinical evidence that immobilization of the TTJ (>140 degrees) successfully treat the CCT injury or degenerative tendinopathy in the
veterinary literature, the strain generated in the anastomosis site is presumably less than 49N in clinical scenario, because higher risk of tenorrhaphy failure would be suspected if it was > 49N. Because there is clinical evidence that immobilization of the TTJ (>140 degrees) provides adequate healing of the tenorrhaphy, we speculated that the TTJ ROM of 140-170 degrees (30 degrees of free ROM) would be safe with minimum strain to create gap formation at the anastomosis site. If hyperextension of the FTJ (>140 degrees) is avoided, the TTJ ROM of 30 (140-170) degrees is possible with strict case rest. Moreover, the FTJ will likely be more flexed to adjust the affected limb due to hyperextended affected limb during ambulation as a compensatory mechanism in clinical setting (personal observation). These results provided the assumption that the strain generated at the anastomosis site would not exceed 49N at the normal standing angle if the TTJ flexion (< 140 degrees) was avoided during healing of the tendon. The gap was measured in eight pelvic limbs following the kinematic study. Additional two limbs were evaluated for the effect of an intact SDFT in this study, where transection of the GMTU was performed 2cm proximal to the insertion due to ease of tenorrhaphy by interference of intact SDFT at the calcaneal insertion. The result revealed a gap was formed at the FTJ angle of 135 degrees with the TTJ angle at 125 degrees. No gap formation was observed when the FTJ angle was < 120 degrees, regardless of the TTJ angles. Therefore, the TTJ ROM is primarily the limiting factor. When the FTJ is < 135 degrees, there is no limitation of the TTJ ROM, but when the FTJ is > 135 degrees, the TTJ angle must be > 125 degrees, and therefore the FTJ ROM is the additional factor. When the FTJ angle is at 150 degrees with the TTJ angle at 140 degrees, gap formation developed, and further angle combinations could not be evaluated due to tenorrhaphy failure. The angle combination of the limb could not be maintained during the kinematic study, indicating the strain to the CCT was less than the load of tenorrhaphy failure in any combinations performed for the kinematic study. There was no difference between the locations of
anastomosis or the effect of intact SDFT. Clinically mild plantigrade posture with digit flexion during weight bearing is recognised when the GMTU is affected without SDFT damage. This study demonstrated that the SDFT does not have a protective effect for intact GMTU.

Moores et al. demonstrated that 44N and 31N of load caused 1mm gap formation, and 56N and 49N caused 3mm gap formation in a tendon anastomosis using a standard or modified three-loop pulley suture technique respectively in a cadaveric study. In our study, there was no difference between standard or modified three-loop pulley sutures, and both failed at a FTJ angle of 135 degrees and TTJ angle of 125 degrees. In our study, keeping 1mm of the gap was not possible. The 1mm gap progressed to 3mm gap within a few seconds at the FTJ angle of 135 degrees and TTJ angle of 125 degrees. It may be critical that the FTJ angle is between 120 and 135 degrees and the TTJ angle between 125 and 140 degrees. More detailed angle analysis may be required to detect which TTJ angle is optimal. Increasing load to the foot while simultaneous measuring of the TTJ angle may determine the point of failure. Use of a detailed strain measuring experiment of these joint ROM (e.g., using a strain gauge or tensometer) may validate the concept. However, the mathematical calculation correlated well to the ex vivo data, and the working length of the GMTU relative to FTJ and TTJ angles could be predicted. During stance phase, the ROM of the FTJ was 120-140 degrees (20 degrees of ROM), and the TTJ 130-160 degrees (30 degrees of ROM), and these were defined as blue lines, and the risk of gap formation was indicated as red lines in Figure 23. The only risk combination of the FTJ and TTJ would be in the range where the FTJ is between 135 and 140 degrees and the TTJ is at 130 degrees during stance phase. This is the risk of developing higher strain due to impact from the ground when a dog strikes the ground. Therefore, the angle combination should be avoided to minimize the strain to the CCT. The FTJ angle (135-140 degrees) is the normal standing angle of a typical dog, but the TTJ is
usually 140 degrees.\textsuperscript{39} One of ideas to avoid such force would be development of an apparatus to move the FTJ and TTJ synchronously, allowing ROM during gait. An ESF construct with controlled ROM using hinges and stoppers could be constructed to achieve this aim. Based on our results, 15 degrees of free ROM of the TTJ (155-170 degrees) without consideration of the FTJ, and 30 degrees of free ROM of the TTJ (140-170 degrees) is confidently applicable from immediately after surgical anastomosis of the GMTU in the canine cadaveric limb if the FTJ does not exceed 140 degrees. Modified ESF with some sort of hinge or similar device may be able to apply instead of conventional immobilization technique to mobilize the TTJ. However, such apparatus does not consider any stress riser, construct failure or bone fractures associated with dynamization due to the impact from mobile nature of such constructs.

Full range of motion of the TTJ could be allowed if the FTJ ROM synchronized to the TTJ ROM. Fifty percent of original strength is achieved 6 weeks post tenorrhaphy\textsuperscript{1} and this is enough to maintain the anastomosis during physiologic force.\textsuperscript{13,50} Wilson \textit{et al.} demonstrated tenorrhaphy failure (3mm gap formation) of the gastrocnemius tendon occurred after approximately 4mm of tendon elongation in three-loop pulley suture technique (8mm in the double Krackow suture technique).\textsuperscript{51} For a few weeks post tenorrhaphy, the anastomosis site has to be dependent solely on suture strength.\textsuperscript{12} To prevent early postoperative gap formation, the three-loop pulley suture can be supported with extra locking loop sutures,\textsuperscript{12} or double modified Krackow suturescan be used, which provides higher failure load compared to the three-loop pulley suture in an ex vivo study.\textsuperscript{51} Adjuvant sutures may be considered to improve the tenorrhaphy, and further mobilization of the TTJ may be possible.

The FTJ is a complex joint, and the joint has movement such as rotation, compression, distraction, torsion, and sliding.\textsuperscript{52} There is no permanent center of rotation in the FTJ because the femoral reference point moves constantly depending on the angle of the FTJ.\textsuperscript{52} To
simplify the FTJ model for the study, the femoral reference point was identified radiographically. The femoral reference point is located in the middle of the femoral condyle.\textsuperscript{46} The femoral reference point was determined in the lateral projection of the pelvic limb radiographs. On the other hand, the CR of the TTJ is located at the center of the talus all the time.\textsuperscript{47} However, the GMTU terminates at the proximal calcaneus, and therefore, the length and direction of the GMTU axis varies all the time, and moves constantly depending on the FTJ and TTJ angles. Although the angle between the line of the supracondylar tuberosity-to-fabella and the line of the fabella-to-GMTU insertion changes during ROM of the FTJ, the distance between the fabella and supracondylar tuberotisity did not change during various ROM. Because the GMTU is biarticular, changes around the FTJ will allow changes in TTJ ROM for the same GMTU length.

\textbf{Figure 24.} A series of radiographic exposures in one film showing the FTJ ROM and medial fabellar movement. Note ICR moves with FTJ ROM and the origin of the GMTU moves as well (\textbullet) and measurement points of the GMTU origin (\textcircled{i}). The red arrow (\textblacktriangleleft) is the difference of the interarticular axis length (T) during ROM of the FTJ.
There are limitations to this study. The methodology used in this study is a simplified approximation of the center of the femoral condyle. Moreover, the physiological ROM of the canine pelvic limb was simulated without consideration of any weight bearing effect. The nature of the cadaveric study does not reproduce live muscle-tendon flexibility. Isometric contraction may be a significant factor to consider when tendon anastomosis is performed. In live dogs, the medial head of GMTU was active through 80-85% of the stance phase. During the later phase of propulsive stance, the GMTU passively stretches the active muscle, creating in redirected propulsive force. In chronic tendinopathy, elongation of affected tendon can occur. More importantly, it is not uncommon to resect affected area of more than 2cm from the base of the GMTU insertion to remove the damaged abnormal tissue, achieving better healing and functional recovery. The strain will increase if a large portion of the tendon has to be removed. This study did not consider the calculation of the resected tissue. Lister et al. concluded that isometric contraction of the CCT should take into consideration because immobilization of the TTJ did not change the peak strain in live animals. However, they placed a transarticular ESF in normal standing angle, presumably 140 degrees. If the FTJ was > 135 degrees, the strain at CCT would increase in vivo as in this mathematic equation provided in this study, based on the cadaveric limb model. The peak strain was not significantly different from the control. TTJ transarticular immobilization in hyperextension (>150 degrees) may reduce extra strain even during the stance phase of the gait as minimal effect of muscle contraction if the FTJ angle is <135 degrees, because it will be a short GMTU working length, that may not be a risk of anastomosis failure.

The CCT is a complex structure regulating flexion of the FTJ and TTJ, but also phalangeal joints (SDFT inserts at P2). The GMTU is one component of the CTT, and more complicated biomechanics are present in the structure. In this study, the method was
simplified to focus on the GMTU. This is a simplified cadaveric study of complex kinematics without consideration of kinetics, and therefore, the data should be interpreted with caution.

Our cadaveric kinematic study concluded that 30 degrees of free ROM of the TTJ is possible without significant risk of anastomosis failure and decreased articular morbidity of the TTJ. Synchronized movement of the FTJ and TTJ simultaneously may allow nearly full physiologic ROM of the FTJ and TTJ simultaneously. More detailed *ex vivo* and *in vivo* studies may be warranted to investigate improved immobilization techniques to manage CCT repair.
4 Conclusions:

Chapter 2 evaluated the efficacy of various types of tibiotarsal transarticular immobilization techniques. This study revealed no statistical differences between techniques in their ability to provide effective immobilization of the TTJ in hyperextension at single static loading of 200N. Surgeon preference and client/patient factors are therefore valid components to determine in the clinical setting which technique is used for TTJ immobilization. In Chapter 3, the working length of the GMTU was determined at a range of FTJ and TTJ angles. The gastrocnemius muscle has a wide base origin which is located between the supracondylar tuberosity and fabella. The muscle curved distally after the fabella, becoming the tendinous part of the gastrocnemius muscle, inserting at the proximal calcaneus. Therefore, the entire GMTU is curved. Moreover, the muscle connects the distal femur to the calcaneus, bypassing the tibia. In this study, the model was simplified and measurement of the GMTU was considered as a straight line. A mathematical formula was created to predict the behavior of the GMTU. The result indicated that 10-15 degrees of ROM of the TTJ might not cause strain at the anastomosis of the GMTU without concerning of the FTJ ROM. The data also suggested that mobilization of the TTJ up to 30 degrees (the angle range of 140-170 degrees) during immobilization after tenorrhaphy might be safe. Furthermore, if the FTJ is synchronized with the TTJ, the range of motion of the TTJ could have no limitation. If the theory is applied to clinical cases, the negative effect of the prolonged tibiotarsal immobilization may be reduced. In clinical setting, implant failure can be a problem due to larger motion in the joint, creating abnormally higher force at the immobilization system. A future study using repetitive cyclic mechanical testing may reveal the feasibility in clinical situation. The effect of the introduced motion at the TTJ may be able to compare the clinical outcome and length of functional recovery to the conventional approach. The next step is to measure tendon moment arm of the gastrocnemius tendon using the radiographs from the
chapter 3 and analysis of the data. Transarticular immobilization application and testing of cyclic and absolute failure of the developed immobilization system is required to validate the current immobilization techniques. In future, development of new immobilization technique and cyclic mechanical testing of the system is warranted.
5 References:


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