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Kinetic Analysis of Canine Gait on the Effect of Failure Tendon Repair and Tendon Graft

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Abstract

Kinetic analysis of canine gait has been extensively studied, including normal and abnormal gait. However, no research has looked into how flexor tendon injury and further treatment would affect the walking pattern comparing to the uninjured state. Therefore, this study was aimed to utilize a portable pressure walkway system, which has been commonly used for pedobarographic and kinetic analysis in the veterinary field, to examine the effect of a failed tendon repair and tendon graft reconstruction on canine digit kinetics during gait. 12 mixed breed (mongrel) hound-type female dogs were included in this study and 2nd and 5th digits were chosen to undergo flexor tendon repair and graft surgeries. Kinetic parameters from the surgery leg in stance phase were calculated. From the results, after tendon failure repair, decrease of weight bearing was seen in the affected digits and weight bearing was shifted to the metacarpal pad. After tendon graft reconstruction, weight bearing returned to the affected digits and metacarpal pads. Slight alteration in peak pressure and instant of peak force were identified, but it was estimated to have little influence on post-reconstruction gait. This study could serve as a reference in evaluating canine digit function in flexor tendon injury for future studies.

Keywords

Portable pressure walkway system; Canine gait; Flexor tendon; Tendon failure repair; Tendon graft

Introduction

The canine model has been a common animal model for flexor tendon related research. Historically measuring functional outcomes, such as digit work of flexion, adhesion

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Conflict of interest statement

None of the authors has any financial or personal relationships that could inappropriately influence or bias the content of the paper.

formation, tendon gliding ability, healing strength, after tendon repair or reconstruction requires animal sacrifice; it would be ideal if the digit function can be evaluated and monitored in vivo without sacrificing animals. Recent technology by studying the kinematics and pedobarography of canine paw with each individual digit contributions during canine gait may provide a way to evaluate tendon function. Electrogoniometer and 3D motion capture system have been utilized to examine the kinematics both in normal and abnormal canine gait (Adrian et al., 1966; DeCamp et al., 1996; Marsolais et al., 2003). However, it would not be a complete analysis of gait without kinetic outcome, since it gives us an idea of how their body experiences loading. Therefore, force plates were incorporated to analyze the ground reaction force. It was found that the mean force during normal walking of forelimbs was 1.1 times that of body weight and the hind limbs were 0.8 times of body weight (Newton and Nunamaker, 1985). To investigate the methods of differentiating normal from abnormal, a force plate was used to measure contact time, braking, impulsion and ground reaction force in different diseases (Budsberg et al., 1987; Johnston and Budsberg, 1997; Vasseur et al., 1995). For unilateral lameness dogs, walking would result in discomfort and failure to use the injured limb, thus lower braking and impulsion forces (Conzemius et al., 2005; Evans et al., 2003; Schwarz et al., 2017).

Although force plates seem to be ideal for kinetic analysis, it is difficult to differentiate among limbs due to overlap of paw prints especially in smaller breeds with smaller strides (Besancon et al., 2003; Lascelles et al., 2006). In 2003, a group attached a single force sensing resistor to each paw. During dog walking, it was found that 3rd and 5th digital pad (DP) had larger pressure than the metacarpal pad (McP), and MCP had larger pressure than 2nd and 4th DP (Marghitu et al., 2003). Since 2004, scientists started to apply portable pressure walkway systems which are composed of multiple force sensing elements to investigating canine gait, leading to better flexibility of locations, detailed pressure distribution of all paws and the capability of collecting multiple prints in one trial. It was found that walking faster would result in larger peak pressure (Burnfield et al., 2004; Schwarz et al., 2017).

A few studies try to characterize the pressure distribution of the pads in different breeds. In normal forelimbs, for Greyhounds, peak vertical force (PVF) of 2nd DP was lower than MCP and other digits. For Labrador Retrievers, 3rd, 4th & 5th DP were larger than 2nd DP but lower than MCP. No significant differences were found between left and right forelimbs in both breeds (Besancon et al., 2004). PVF in the forelimbs of German Shepherds showed that MCP was larger than other digits (Souza et al., 2013). PVF of normal forelimbs of Pitbulls displayed that MCP being the largest followed by 4th, 3rd & 5th and 2nd DP. In addition, overall PVF was 30% lower in Pitbulls with cranial cruciate ligament rupture in the hind limbs compared to the normal. In addition, PVF in affected MCP was 70% lower than the control (Souza et al., 2014). On the other hand, instead of comparing PVF among different pads, one study divided the paw print in to quadrants and evaluated PVF and the instant of peak force (IPF) in healthy dogs during walking. They found out that in PVF, cranial was larger than caudal and lateral was larger than medial. For IPF, caudal occurred earlier than cranial (Schwarz et al., 2017).

Portable pressure walkway system was considered to be useful in evaluating limb function and loading in canine gait. However, no study has focused on the effect of flexor tendon injury and further tendon graft on canine pedobarography and digit kinetics during gait. Therefore, this study was aimed to encompass a flexor tendon repair failure model followed by tendon graft reconstruction to compare multiple kinetic parameters between affected and non-affected digits in the surgery leg by using a portable pressure walkway system.

Materials and Methods

This study was approved by Institutional Animal Care and Use Committee. Pain medication was given to the dogs after the surgery to minimize their pain.

Animals

12 mixed breed (mongrel) hound-type female dogs were included in this study and started at 20kg of body weight (around 8 months old). All dogs were clinically examined to be healthy and with no signs of injury.

Data Collection

A portable walkway system (emed[®]-x1, Novel, Munich, Germany) was used to collect pedobarographic and kinetic data. With over 25000 sensors in the sensing area ($1440 \times 440 \text{ mm}^2$), the system offered a resolution of 4 sensors/cm² with a sampling frequency of 100Hz. Data were recorded by a commercial software (emed[®]-x1/R, Novel, Munich, Germany) and a video was synchronized and recorded in each trial. For each condition, at least 10 successful trials were collected (Fig. 1).

Study Design

All dogs underwent an acclimation period of two weeks, which included a week of quarantine and a week to get used to the environment and the walkway system before the start of the study. 1–3 days before tendon repair surgery, normal gait kinetic data were collected. Next, a failed flexor digitorum profundus (FDP) repair with scar digit model were created in the 2nd and 5th digits in a randomly selected right or left paw. Following anesthesia, the 2nd and 5th FDP tendons were fully lacerated, and repaired with the modified Kessler technique. The surgery paw was wrapped with a sterile dressing in the wrist flexion position. The dogs were housed in a post-operative recovery room until fully recovered from anesthesia, and then dogs were moved to their regular cage with a customized dog jacket. Jackets were used to keep the operative paw non weight-bearing until the incisions heal in about 10–14 days. Then, the jacket was removed and the dogs were allowed full cage activity. This unconstrained active activity resulted in the repaired tendon rupture with scar digit. This repaired tendon failure model is a good animal model to simulate a clinical scenario to study flexor tendon reconstruction (Tanaka et al., 2007; Wu et al., 2015; Zhao et al., 2014). The failure outcome was also proven by using fluoroscope to observe the gap on the failed repaired tendon in vivo in a previous study (Zhao et al., 2010). Gait kinetic data were acquired on the 4th and 6th week after failure repair surgery (Fig. 2).

1–3 days after the data collection of 6th week, tendon reconstruction was implemented. Dogs had a FDP tendon reconstruction using a single stage extrasynovial autograft using the peroneus longus tendons harvested from both hind limbs. The peroneus longus tendon was chosen because it is a stabilizing tendon that has been used clinically for tendon grafts with no effect to the patient. Past graft studies have used this tendon with no hind limb deficit being observed in dogs. The surgical paw was wrapped with a sterile dressing in the wrist flexion position. Dogs were housed post-operatively in a recovery room until fully recovered from anesthesia then dogs were moved to their regular cage with a special dog jacket to prevent weight bearing. Five days post-op, passive synergistic therapy was started. Passive movement of full range of motion of the elbow, wrist and 2nd and 5th digit was performed with each joint being stabilized and then brought from full extension to flexion and it took about 5–10 minutes to complete once daily until 6th weeks post-op. For 6th–12th weeks, post-op passive synergistic therapy was continued and in the meantime, jackets were removed twice daily for 10 minutes and full cage activity was allowed under supervision. After 12 weeks, post-op jackets were removed and full cage activity was allowed. At this time, Gait kinetic data were measured on the 13th, 15th, 19th and 23rd week after tendon graft (Fig. 2).

Data Reduction

Stance phase data of all trials were analyzed and individual pads were masked by the commercial software (Novel Projects, Novel, Munich, Germany). All five pads in contact with the ground were included which were metacarpal pad (McP), 2nd to 5th digital pad (DP) (Fig. 3). The related kinetic parameters were calculated and organized through a custom-made MATLAB program (MathWorks, Natick, Massachusetts) including those described below. Peak vertical force (PVF) was calculated as the maximum value of vertical force and it indicated the magnitude of weight bearing. On the other hand, peak pressure (PP) was the maximum value of pressure in stance phase, which served as weight bearing indicator similar to PVF but taking contact area normalization into account. Moreover, instant of peak force captured the time point when PVF happened in stance phase, showing temporal changes before and after surgery. Finally, by taking the integral of pressure-time curve, pressure-time integral (PTI) was calculated and the accumulative effect of plantar pressure over time was identified. According to a previous study about the calculation of PTI, a modified PTI was recommended by using force-time integral divided by contact area, which was said to be less correlated to PP thus might provide more information (Melai et al., 2011).

Statistical Methods

Peak vertical force (PVF), peak pressure (PP), instant peak of force (IPF), and pressure-time integral (PTI), as the outcome measures, were calculated as mean $\pm$ SE (standard error). SPSS (IBM, Armonk, New York) was utilized to conduct statistical analysis. One-way ANOVA of repeated measures was chosen to analyze statistical differences among different selected conditions (Table 1). Normal distribution was confirmed using Shapiro-Wilk test. Sphericity was checked using Mauchly's Test and if the assumption was broken, Greenhouse-Geisser correction was used to adjust the degrees of freedom for the effect. A *p*-value of 0.05 was set as the significance level.

Results

All repaired FDP tendons in the first phase were confirmed ruptured with the same pattern which presented the proximal tendon stump retracted into palm level, scar formation within the flexor sheath.

For peak vertical force (PVF), an overall significant difference was found in McP ($p = .000$), 2nd ($p = .041$) and 5th DP ($p = .001$), respectively and the results are shown in Fig. 4. After failure tendon repair (TR2), significantly higher PVF was found comparing to the normal in McP. For affected DPs, PVF was found to be lower than the normal in 2nd DP. In addition, significantly lower McP PVF was found in the first test after tendon graft reconstruction (TG1) than TR2. Moreover, in the last test after tendon graft reconstruction (TG4), lower PVF was found in McP and higher PVF was found in 5th DP with significant differences. No significant difference was found among conditions in 3rd and 4th DP. For instant of peak force (IPF), an overall significant difference was found in 2nd ($p = .002$) and 5th DP ($p = .023$), respectively and the results are shown in Fig. 5. No significant pair-wise differences were seen except that the IPF of 2nd DP was lower in TG4 than both TR2 and the normal.

For peak pressure (PP), an overall significant difference was found in McP ($p = .001$), 2nd ($p = .016$), 3rd ($p = .033$), 4th ($p = .006$) and 5th DP ($p = .000$), respectively and the results are shown in Fig. 6. Significantly higher PP was found in TR2 than the normal in McP. For affected 2nd and 5th DP, PP was found to be lower than the normal in 2nd DP. In addition, significantly lower McP PP and higher 2nd DP PP were found in TG1 than TR2. Moreover, significantly higher 5th DP PP was found in TG4 than TG1, TG2 as well as the normal. For non-affected 3rd and 4th DP, higher PP was found in TG4 than TG1 with significant difference and PP of 4th DP was particularly higher in TG4 than the normal. For pressure-time integral (PTI), an overall significant difference was found in McP ($p = .004$) and the results are shown in Fig. 7. Significantly decrease was found in PTI of 2nd and 5th DP in TR2 than the normal. In addition, PTI of McP showed significantly a lower value in TG1 than TR2.

Discussion

Functional outcome was successfully examined in the affected paw by the portable pressure walkway system. After failure tendon repair, larger PVF and PP were found compared to the normal in McP. For affected 2nd and 5th DP, PVF and PP were found to be lower than the normal and it was especially significant in 2nd DP. There was also a significant decrease in the PTI. This data demonstrated that following 2nd and 5th FDP tendon rupture with dysfunction of the relative digits, the pedobarographic pattern of the surgical paw has been altered by shifting more weight bearing from injured digits (2nd and 5th) toward to the McP. In the first test after tendon graft reconstruction, comparing the failure model, PVF, PP and PTI were found to be lower in McP. For affected 2nd and 5th DP, PVF and PP generally displayed higher values than failure model. This indicated that after 13 weeks of tendon reconstruction, the pedobarographic pattern of the surgical paw improved significantly compared to the failure model. At the 23rd week after tendon reconstruction, PVF decreased significantly comparing to failure model, but no differences were found comparing to the

normal in McP. Moreover, for affected 2nd and 5th DP, PVF and PP were generally higher than failure model and it was particularly significant in 5th DP. PP appeared to be higher than the normal after tendon graft in all DP. However, there was no difference in PTI. Despite there was a decrease in IPF in 2nd DP, the overall outcome displayed that after tendon graft reconstruction, digit function was recovered back to normal pedobarography.

In normal dogs, a few studies have investigated the IPF of each pad and most of them concluded that McP takes place first and followed by other digits (Schwarz et al., 2017; Souza et al., 2014). In our study, it also showed similar trend but with more detailed sequence of McP followed by 5th, 2nd, 4th and 3rd DP. Moreover, for PVF, we found that McP was responsible for largest portion of weight bearing followed by 3rd, 4th, 5th and 2nd DP, which was in line with previous studies as well (Besancon et al., 2004; Souza et al., 2013; Souza et al., 2014).

From PVF and PP, after undergoing failure tendon repair, weight bearing of the affected digits of canines was clearly reduced. This resulted from the scar tissue formed on the repaired tendon. For DP, the weight bearing consisted of both active and passive. The scar tissue on the affected tendons would compromise the active weight bearing, thus making it hard to perform digit movement. A previous study investigating the effect on vertical force of cranial cruciate ligament rupture found out that comparing to healthy limbs, affected limbs manifested lower vertical force (Souza et al., 2014). Moreover, after flexor hallucis longus was transferred, loss of active flexion in hallux was observed and plantar pressure and force were reduced in hallux (Hahn et al., 2008; Richardson et al., 2009). This phenomenon of decrease PVF and PP was thought to be commonly seen in injured dogs. For PTI, it showed that comparing to the normal PTI was significantly reduced in both affected pads, indicating a protection mechanism to keep those two pads from high cumulative pressure. On the other hand, the shifted weight bearing was thought to be transferred to McP, leading to increase of PP and PVF. Since there was no change in both 3rd and 4th DP, McP was solely responsible for compensating the weight bearing loss of the affected pads.

In the first test after tendon graft reconstruction (TG1), we could see an obvious decrease in the PVF and PP of McP. The time point of this test was the first week that the dogs got out of restricted movement and started full activity. The leg muscles might turn weak due to the 12-week immobilization and scarce exercise, thus weight might be shifted to other unaffected limbs. Body weight distribution and muscle strength and utilization play an crucial role in the symmetry and spatial-temporal parameters (Light et al., 2010). In addition, McP weight bearing is solely contributed passively by the leg. Therefore, at this time point, although the compensating loading mechanism was not spotted after tendon graft, it still displayed lower weight bearing comparing to the normal. However, as the time went by with full activity, this phenomenon gradually disappeared and no differences were found between the weight bearing of the last test (TG4) and the normal.

For the affected 2nd and 5th pads in TG1, weight bearing was found to be larger than that in failure model from the results of PVF and PP. This indicated that active loading exerted by the tendon was back to functional state due to the effect of tendon graft reconstruction. Although the influence of immobilization might weaken the muscles controlling digit

movement, comparing to the results of failure model, immobilization seemed to have little effect on the functional outcome. As the healing process went by, weight bearing still remained in a similar higher level, suggesting that the efficacy of tendon graft reconstruction sustained and helped the dogs regain digital function. PVF and PP in TG4 were generally higher than that in failure model. In addition, larger PP was also found comparing to the normal. By taking only PP into consideration, this might be interpreted as an alteration in pad pressure pattern. However, if we take a look at the results of PTI, which was an indicator of cumulative pad pressure, there was no significant difference found between TG4 and the normal. Therefore, the influence of this alteration might be considered as unharmed to post-surgery exercise.

Aside from the magnitude of weight bearing, it is also essential to look at the temporal parameter for the timing of occurrence. In general, IPF displayed no significant differences between any two of the normal, failure model and tendon graft reconstruction of all pads except 2nd DP. 2nd DP IPF of TG4 was found to happen earlier than that in failure model and the normal, which indicated that after tendon graft, occurrence full weight bearing to 2nd DP moved ahead in the stance cycle. Although the pattern of gait was altered, from a normal gait point of view, it was still within the period from mid stance to terminal stance. Therefore, we would assumed that this alteration would not bring too much of a side effect of after tendon graft reconstruction during exercise.

This study focused mainly on the affected leg and the pedobarographic and kinetic distribution in that foot. Therefore, there might be limitations of not fully discussing the pattern of all four legs. In addition, the results of this study are applicable only to the dogs that have similar body type due to the homogeneity of the sample pool. However, this study might be able to provide a reference in evaluating digit functions. Although mankind being a bipedal animal, it is unlikely to evaluate the finger function after surgery using portable walkway system. However, with this workflow successfully built up, digit function could be evaluated in vivo and assist the surgeons to test or practice new surgical techniques without sacrificing the animal in order to investigate more on the effect of flexor tendon repair and reconstruction.

Functional outcome of the normal, digital tendon failure model and tendon graft reconstruction was completely analyzed in the affected paw with pedobarographic analysis. After failure tendon repair, weight bearing was discovered to decrease in the affected pads comparing to normal and shifted to McP as a compensation mechanism. After tendon graft reconstruction, tendon function was restored and weight bearing of the affected pads was gradually recovered. Though it turned out that in the affected pads, the peak pressure was larger and instant of peak force was earlier after grafting, it was estimated to have little influence and side-effect in terms of cumulative pressure and gait sub-phases.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.
Software interface for dog gait kinetic data collection with a synchronized video camera

Figure 2.
Timeline of the experimental workflow and specific time points

Figure 3.
Canine forelimb anatomic structure

Figure 4.
Peak vertical force (PVF) of all pads and conditions

Figure 5.
 Instant of peak force (IPF) of all pads and conditions

Figure 6.
Peak pressure (PP) of all pads and conditions

Figure 7.
 Pressure-time integral (PTI) of all pads and conditions

Table 1

Condition lists and abbreviations

Abbreviation	Condition
NOR	Normal
TR1	4 th week after failure tendon repair
TR2	6 th week after failure tendon repair
TG1	13 th week after tendon graft
TG2	15 th week after tendon graft
TG3	19 th week after tendon graft
TG4	23 rd week after tendon graft