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Analysis of the Gliding Pattern of the Canine Flexor Digitorum Profundus Tendon through the A2 Pulley

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Abstract

Friction between a tendon and its pulley was first quantified using the concept of the arc of contact. Studies of human tendons conformed closely to a theoretical nylon cable/nylon rod model. However, we observed differences in measured friction that depended on the direction of motion in the canine model. We hypothesized that fibrocartilaginous nodules in the tendon affected the measurements and attempted to develop a theoretical model to explain the observations we made. Two force transducers were connected to each end of the canine flexor digitorum profundus tendon and the forces were recorded when it was moved through the A2 pulley toward a direction of flexion by an actuator and then reversed a direction toward extension. The changes of a force as a function of tendon excursion were evaluated in 20 canine paws. A bead cable/rod model was developed to simulate the canine tendon-pulley complex. To interpret the results, a free body diagram was developed. The two prominent fibrocartilaginous nodules in the tendon were found to be responsible for deviation from a theoretical nylon-cable gliding around the rod model, in a fashion analogous to the effect of the patella on the quadriceps mechanism. A bead cable/rod model qualitatively reproduced the findings observed in the canine tendon-pulley complex. Frictional coefficient of the canine flexor tendon-pulley was 0.016 ± 0.005 . After accounting for the effect created by the geometry of two fibrocartilaginous nodules within the tendon, calculation of frictional force in the canine tendon was possible.

Keywords

Tendon; Pulley; Friction; Canine Model

Introduction

Degenerative tendon disorders, such as trigger digit and deQuervain disease, are of increasing incidence (Barr, et al. 2004, Mota, et al. 2000–2001) and result in significant morbidity (Wang, et al. 2006). While these conditions are common, the underlying pathology is unclear (Wang, et al. 2006, Sharma and Maffulli 2005). Friction between the tendon and pulley may be an important etiological factor. To understand the interaction between tendon and pulley, a testing

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device to measure friction has been described by An, et al. 1993 and Uchiyama, et al. 1995, followed by Moro-oka, et al. 1999. Recently, in vivo measurement of friction has also been introduced (Schweizer, et al. 2003).

In this device the concept of a cable around a fixed mechanical pulley was used to interpret the measurement values. In an idealized model, using a nylon cable and a nylon rod as the pulley, the force difference in the cable on either side of the rod is constant throughout excursion for a given arc of contact and it is always recorded as a positive value. The difference is, in effect, the force dissipated by friction between the cable and the rod. This model can be used to calculate friction force and the friction coefficient. We have applied this model to the tendon-pulley interaction in the human hand and found that, although there were some minor deviations from the nylon cable-rod model, the friction force could be calculated as predicted by the model (Uchiyama, et al. 1995).

Experiments to study tendon friction in vivo after experimental injury are usually done using a canine model (Zhao, et al. 2002, Sun, et al. 2004, Tanaka, et al. 2006, Tanaka, et al. 2006, Zhao, et al. 2006). Unlike the human situation, the canine tendon contains two distinct fibrocartilaginous nodules, through which the tendon fibers run in a longitudinal direction (Fig. 1) (Lin, et al. 1989). The purpose of this study was to measure the gliding pattern and the force difference of the canine flexor digitorum profundus tendon across the A2 pulley and to determine what modifications, if any, in the cable-rod model might be needed to adequately explain those observations.

Materials and Methods

Hind paws were harvested from 20 dogs sacrificed for other, IACUC approved, purposes. Twenty digits were disarticulated through the MP joint.

Experiment 1

The canine flexor profundus tendon through the A2 pulley.

Ten digits were used. The excursion of the flexor profundus tendon was determined as follows: with the digit fully extended manually, the lateral side of the flexor profundus tendon was marked at the distal edge of the A2 pulley. The tendon was then pulled proximally until the digit would flex no further and the flexor profundus tendon was marked at the distal A2 pulley edge. The distance between the two markers was considered the tendon excursion of the digit. Each specimen was then dissected so as to leave only the A2 pulley with its bony insertion and the flexor profundus tendon. To compare with the human model, only the A2 pulley with its bony attachment and the flexor profundus tendon were used. Each specimen was then mounted on a testing device with the volar side of the specimen upward and the proximal side toward the actuator. The proximal end of the tendon was connected to a ring load transducer (F2) and a mechanical actuator; the distal end of the tendon was connected to a ring load transducer (F1) and a 4.9 N weight. With the angle fixed at 30 degrees each (α and β in Fig. 2) and the tendon positioned at its maximum extension position as determined by the previously placed markers, the tendon was moved toward the actuator (flexion) with a velocity of 2 mm/sec for the predetermined excursion while F1, F2 and excursion were recorded at a sampling rate of 10Hz (Fig. 3A). The tendon was then allowed to move in the opposite direction by reversing the actuator until it returned to its original position (extension) while the same parameters were recorded (Fig. 3B). This trial of flexion and extension was repeated three times. The effect of excursion on F1 and F2 was evaluated qualitatively to observe the changes of force as a function of excursion. For 2 specimens out of 10, with the angle set at 30 degrees each, the tendon was translated proximally from the position when the proximal nodule was distal to the A2 pulley until the distal nodule passed completely beneath the A2 pulley. This procedure was included

to examine the effect of an unphysiologically long tendon excursion on the pattern of F2 and F1.

Experiment 2

The canine flexor profundus tendon under a Plexiglas rod

To see if the tendon was responsible for the characteristic gliding pattern observed in Experiment 1, the tendon was taken out of the A2 pulley and passed under a Plexiglas rod (diameter 22.3 mm) (Fig. 2B). Two flexor profundus tendons used in experiment 1 were used. The tendon excursion was determined so that the rod contacted approximately the same part of the tendon as in the tendon-pulley setup. The angles were set at 30 degrees each (α and β in Fig. 2) the tendon was translated proximally and the parameters described above were recorded. The effect of excursion on F1 and F2 was evaluated qualitatively.

Experiment 3

A bead-cable unit passed under a rod

Since the canine flexor profundus tendon consists not only of tendon fibers, but also of two fibrocartilaginous nodules, a bead (Plexiglas 7.9 mm diameter) and a cable (Dacron 0.5 mm diameter) were used to simulate the tendon. The bead corresponded to the nodule and the cable to the tendon fibers. As we tried three different bead sizes and found similar gliding patterns with all, only the data for the 7.9 mm sized bead is presented here. To simplify the model, we used only one bead. In this set of experiments we used an additional six components load transducer into which the Plexiglas rod (25.3 mm diameter) was mounted. The reaction force between the rod and the bead-cable unit could then be calculated using the vector summation of the two measured force components in the plane of interests. The angle of α and β were set at 30 degrees each.

The bead was placed between the F1 load cell and the rod (Fig. 2C). The bead-cable unit was translated toward the actuator under the Plexiglas rod. Data collection began at a position before the bead contacted the Plexiglas rod and continued until the position when the bead lost contact with the rod. F1, F2, normal force, side force and corresponding excursion were recorded. F1, F2, side and normal forces were plotted against excursion. The normal force vector and the side force vector formed the resultant reaction force between the rod and the bead-cable unit. Using this data, a free body diagram of the bead-cable unit was created for several excursion points, to explain the observed values of the force difference between F2 and F1 for the tendon pulley experiment. The free body diagram was made for the following conditions; a) when there was contact only between the cable and the pulley (excursion 1), b) when the bead came into contact with the rod, while the cable was still in contact with the rod (excursion 2), c) when only the bead was in contact with the rod (excursion 3), d) when the bead was in the opposite side and once again both bead and cable contact was achieved (excursion 4).

Experiment 4

Calculation of friction force and friction coefficient between the flexor tendon and the pulley of the canine model.

Ten digits were used. With the angle of α and β fixed at 10 degrees each, the tendon was moved proximally and then reversed to move the tendon distally to the original position. F2, F1 and corresponding excursion were recorded. This trial was repeated three times. Then the angle of α and β was changed up to 30 degrees each in 10-degree increments. The same measurement was repeated at each angle.

Results

Experiment 1

The canine flexor profundus tendon through the A2 pulley.

The tendon-pulley contact took place along the segment of tendon with the fibrocartilaginous nodules. In flexion, F2 started at a lower value than F1. As excursion progressed, F2 increased almost linearly. The calculated force difference F2-F1 was negative in each case. Above 5 mm excursion, it was positive as the distal nodule came into the A2 pulley. In extension, F2 decreased linearly as motion progressed (Fig. 4). When the tendon was translated for an unphysiological long excursion toward an actuator, F2 changed significantly depending on the relationship of the fibrocartilaginous nodule to the pulley. As the proximal nodule came into the A2 pulley, F2 increased linearly ('a' in Fig 5). F2 decreased to a value less than F1 as the proximal nodule came out of the pulley (b) and then increased again to a value greater than F1 as the distal nodule came into the pulley (c). As the distal nodule came out of the pulley, F2 again decreased (d).

Experiment 2

The canine flexor profundus tendon under the Plexiglas rod.

In flexion, F2 was less than F1. As excursion progressed, F2 increased (Fig. 6). Above excursion 9 mm, F2 was greater than F1 as the distal nodule came in contact with the rod. In extension, F2 decreased linearly as excursion returned and the value of F2 was less than that in flexion.

Experiment 3

The bead-cable unit passed under the rod.

From experiment 1, the average of F2-F1 for the whole excursion was calculated to be negative in flexion. This appeared to be related to the effect of the nodules of fibrocartilage. Similarly, when the bead came in contact with the rod, F2 increased (excursion 6–18 mm in Fig. 7). As the bead passed beyond the rod, F2 quickly decreased to a value less than F1 (excursion 18–33 mm), followed by a slow increase as cable-rod contact continued (excursion 33–47 mm). Free body diagrams of the bead-cable unit at four excursion points were developed (Fig. 8). At the point of excursion 1 (Fig. 8A), the reaction force faced inferiorly. At the point of excursion 2 (Fig. 8B), the reaction force directed toward the bead and F2 was greater than F1. At the point of excursion 3 (Fig. 8C), the reaction force faced inferiorly toward the bead and F2 was almost equal to F1. At the excursion 4 (Fig. 8D), the reaction force faced toward the bead and F2 was smaller than F1, recording a negative force difference between the F2 and F1. The direction of the reaction force was approximately toward the bead as long as the bead remained in contact with rod. In the model, we eliminated the force due to geometry by adding F2-F1 for flexion to F1-F2 for extension. The mean friction force was then half of the difference of F2 in flexion and extension. To calculate a frictional coefficient, we added 4.9N to frictional force and then divided by F1. The natural logarithm was taken and was plotted against the angle (in radians). A line was fitted using a least squares method and the resulting slope was deemed to be the frictional coefficient.

Experiment 4

Calculation of friction force and friction coefficient between the flexor tendon and the pulley of the canine model.

The mean frictional force of flexion for a whole excursion ranged from 0.015N to 0.13N, depending on the angle. Frictional coefficient ranged from 0.008 to 0.023, mean 0.01557 ± 0.00515 (correlation coefficient=0.883–0.995, mean 0.961 ± 0.03).

Discussion

We found that F2 increased linearly as excursion progressed in flexion, while F2 decreased linearly in extension for the canine model. Also, the force difference F2-F1 of the canine flexor digitorum profundus tendon across the A2 pulley, which in our ideal model and in the human studies was represented frictional force, was found to be negative, clearly impossible, as friction cannot be negative. In attempting to understand this phenomenon, we began to suspect that the prominent fibrocartilaginous nodules in the canine flexor tendon might be functioning in a fashion analogous to the patella and were gratified to have this impression supported by the bead-cable rod model we then developed. This model qualitatively showed a quite similar curve pattern of F2 to the canine tendon-pulley complex. We concluded that the characteristic curve pattern of F2 in the canine tendon-pulley complex was due to the two fibrocartilaginous nodules in the tendon.

The prerequisite for calculation of a pure friction force using the concept of arc of contact is that F2 stays constant throughout tendon/cable excursion. In other words, the reaction force between the cable-like material and the rod-like material must always be in the same direction. A cable-Plexiglas rod model is ideal to calculate pure friction. This concept of arc of contact, which simulates reasonably the human situation, cannot be directly applied to the canine flexor profundus tendon-pulley complex. For the canine tendon-pulley, the bead effect described above is always dominant. Furthermore, observation also reveals that the canine A2 pulley is flat in the sagittal plane (Okuda, et al. 1987), not an arc of a circle like the human A2 pulley (Lin, et al. 1989). Therefore, in the canine model F2-F1 is not analogous to a rod and cable and does not therefore directly reflect the friction force between the tendon and the pulley.

The free body analysis was helpful in explaining the negative value of force differences across the Plexiglas rod. The magnitude of the negative value depended on the position of the bead and the angles. If these observations are taken into account, we believe that the observed force pattern of the canine tendon-pulley complex can be explained. The tendon excursion takes place so that tendon pulley contact occurs between the two nodules. The proximal edge of A2 pulley is located at the distal edge of the proximal nodule. This relationship corresponded to the position where the bead was beyond the lowest part of the rod. As the excursion of the canine tendon progressed in flexion, the distal nodule came into the A2 pulley, which altered gliding resistance as recorded by F2. For extension, the same explanation could be applied. The varying location of the contact area between the fibrocartilaginous nodules of the flexor tendon and the A2 pulley is the primary determinant of the variation observed in F2 as compared to an idealized cable-rod model. The findings that we observed could be explained if the fibrocartilaginous nodules are considered to behave like a bead. During excursion of the flexor profundus tendon in the canine model, one of the two fibrocartilaginous nodules is always in contact with the A2 pulley.

Although the magnitude of the force and the anatomy are different from the tendon-pulley complex, the same phenomenon is observed in the patellofemoral joint. The fibrocartilaginous nodule of the canine tendon corresponds to the patella and the tendon fibers to the quadriceps tendon and the patellar ligament. A force analysis in the quadriceps tendon and patellar ligament as a function of knee flexion has shown that the shifting location of patellofemoral contact area determine the force ratio of the two tendons (Ahmed, et al. 1987, Huberti, et al. 1984). One of the studies showed that the ratios in the two tendons varied from 0.7 to 1.27 (Huberti, et al. 1984). In active knee extension, the force of the patellar ligament can be smaller

than the quadriceps tendon, depending upon the knee flexion angle analogous to our observation of F2 being less than F1 for flexion. We believe that the fibrocartilaginous nodules of the canine flexor tendon affect F1 and F2 in a manner similar to the effect of the patella at the knee.

Although the bead effect is relatively small in the human profundus tendon when compared with the canine specimen, it cannot be totally ignored. The pattern of gliding resistance does vary between the human flexor digitorum profundus and palmaris longus tendons (Uchiyama, et al. 1997). The palmaris longus, a flat extrasynovial tendon, mimics the theoretical cable-rod model more closely than does the flexor digitorum profundus, i.e., with the palmaris longus friction in flexion and friction in extension are similar, while for the flexor digitorum profundus there is a direction difference, although not so dramatic as in the canine model. The question arises as to whether the friction force between the flexor profundus tendon and the A2 pulley of the canine can be calculated in the face of the apparent negative value in flexion.

Theoretically, it is possible. The difference between F2 and F1 consists of a pure friction force and a force due to geometry, i.e., the effect of the fibrocartilaginous nodule. The force due to geometry is equal, but of opposite sign, in flexion and extension. Thus, if the apparent friction in flexion (F2-F1) and extension (F1-F2) are added and the result divided by 2, a reasonable approximation of actual friction force should be achieved. Using this assumption, the magnitude of friction force for the canine tendon pulley interaction in our setup is 0.015N–0.13N, which corresponds reasonably well to the estimated human value of 0.02N–0.3N under similar conditions (Uchiyama, et al. 1995).

We believe the strength of this study lies in the fact that we have directly measured the forces involved in both an animal and idealized model. The limitations relate to the assumptions we have had to make in our two-dimensional free-body diagram for a system which *in vivo* is complex and three-dimensional. We will also need to quantitatively compare the theoretical prediction to the experimental measurement on the bead-cable model to confirm the findings here. Differences of mechanical properties of the tendon fibers and nodules were not simulated, nor was the size differences between the tendon fibers and nodules adjusted when the cable-rod model was developed. Further limitations relate to the fact that our animal model assessed forces of the flexor digitorum profundus against the A2 pulley only. The *in vivo* situation is much more complex, as tendon-tendon and tendon-bone interactions must also be considered.

In conclusion, the measurement of friction in the canine tendon-pulley system is more complex than in an idealized cable-rod model due to the presence of two fibrocartilaginous nodules within the tendon. A modified cable-rod model, incorporating a bead in the cable to simulate a fibrocartilaginous nodule, provides a reasonable simulation of the observations we had made in the canine tendon-pulley system. A free-body diagram analysis helped us to understand the nature of the forces involved and permitted us to develop a way to estimate friction after arithmetically eliminating the component of force due to the geometrical effect of the bead/nodule.

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Figure 1. Mid section of the canine flexor profundus tendon in the sagittal plane (top) and from the volar aspect (bottom). The two distinguished fibrocartilaginous nodules are apparent (asterisk). D: distal, P: proximal.

Figure 2.

Testing device consists of one mechanical actuator with a linear potentiometer, two tensile load transducers, a mechanical pulley on the right of the figure and a weight.

A: The canine flexor profundus tendon is passed through the A₂ pulley.

B: The same tendon as A is passed under the rod. C: A bead- cable unit is passed under the rod.

*: A2 pulley

Figure 3.

Relationship between the canine flexor profundus tendon and the A2 pulley is shown.

A: The A2 pulley partly covers the distal part of the proximal fibrocartilaginous nodule (colored black). The measurement starts from this position.

B: At the end of excursion, the A2 pulley partly covers the proximal part of the distal nodule (colored black).

Figure 4.

The effect of excursion on F1 and F2 in flexion and extension for one representative case is shown. In flexion, F2 starts at a value less than F1. As excursion progresses, F2 increases almost linearly. At the end of the excursion, F2 is greater than F1 as the distal nodule came into the A2 pulley. The resulting gliding resistance is calculated to be negative. In extension, F2 begins greater than F1 and decreases linearly to a value less than F1.

Figure 5.

The effect of excursion on F1 and F2 for the canine tendon-pulley complex when an unphysiologically long excursion is tested. When the tendon is translated toward an actuator (flexion), F2 changes significantly depending on the site of the fibrocartilaginous nodule. As the proximal nodule comes into the A2 pulley, F2 increases linearly (a). F2 decreases down to below F1 level as the proximal nodule comes out of the pulley (b). Then F2 increases up again above F1 level as the distal nodule comes into the pulley (c). As the nodule comes out of the pulley, F2 decreases again (d). Physiological tendon excursion is from 15 mm to 20 or 23 mm at the bottom axis.

Figure 6.

Effect of excursion on F1 and F2 when the canine flexor profundus tendon is translated under the rod. F2 starts at a value less than F1 level and increases linearly as excursion progresses. Above excursion 9 mm, F2 was greater than F1 as the distal nodule came in contact with the rod.

Figure 7.

The effect of excursion on F1 and F2 when a bead-cable unit is translated under the rod. When the bead comes in contact with the rod, F2 increases (excursion 6–18 mm). As the bead passes beyond the rod, F2 decreases to a value less than F1 (excursion 18–33 mm), followed by an increase as cable-rod contact continues (excursion 33–47 mm).

Figure 8.

Free body diagrams of the bead-cable unit at the four excursion points described in Fig. 7.

A: Contact only between cable and rod. At excursion 1, the reaction force faces inferiorly.

B: Bead and cable are in contact with the rod at right side. At excursion 2, the reaction force is directed toward the bead and F_2 is greater than F_1 .

C: Only the bead is in contact with the rod. At excursion 3, the reaction force faces inferiorly toward the bead and F_2 was almost equal to F_1 .

D: Bead and cable are in contact with the rod at the left side. At excursion 4, the reaction force faces toward the bead and F_2 is smaller than F_1 , recording a negative force difference between F_2 and F_1 . The direction of the reaction force is approximately toward the bead as long as the bead remains in contact with rod.