Analysis on the Force Propagation of the Tendon-sheath Actuation in Dexterous Surgical Robots*

Yuanyuan Zhou, Hao Liu, Member, IEEE, Chongyang Wang, and Zhidong Wang, Member, IEEE

Abstract—Tendon sheath actuation is widely used in the minimally invasive surgery (MIS) robotic system, particularly in the single port laparoscopy (SPL) and the natural orifice transluminal endoscopic surgery (NOTES) robots. The force propagation from the proximal end to distal end is the most important characters for the tendon sheath actuation, and the friction is a major problem. In this paper, a classical friction model is presented at first. A series of experiments are carried out to verify the correctness of model. Some factors like the pulling velocity, the tendon diameter and the sheath curvature, which are not considered in the model are also tested in the experiments. The results show that some of these factors also have effect on the friction. A modified friction model is presented to adjust the different tendon diameters.

Index Terms—Minimally Invasive Surgery Robot, Tendon Sheath Actuation, Force Propagation, Friction.

I. INTRODUCTION

Minimally invasive surgery (MIS) is a new type of surgery in the clinical treatment in recent years [1-3]. Compared with traditional surgery, it has less trauma, quicker recovery and many other advantages. Following the direction to minimize the trauma, new types of surgery like single port laparoscopy (SPL) and natural orifice transluminal endoscopic surgery (NOTES) have been developed[4-6]. The SPL and NOTES use only one incision for the surgery, so the trauma are even less and recovery are much quicker [7, 8]. Due to the small size of the incision, SPL and NOTES usually use the tendon sheath actuation [9]. The tendon sheath actuation consists of an actuation wire referred to as the “tendon” which is enclosed inside a hollow coil wire which is named “sheath”.

The tendon sheath actuator can transmit large force while using very small space and mass. It can also transmit the force in any shape on the path. This advantage is especially important for NOTES, because the manipulator of NOTES has to come through the natural orifice such as gastrointestinal tract and the shape of natural orifice is unknown. But the tendon sheath system also brings some problems for the robot control such as the high friction, nonlinear transmission and tendon deformation [10-12]. There are many researchers trying to solve these problems. M. Kaneko [10] developed a method to calculate the friction and the tendon force along the path while the shape is fixed and the curvature is constant. G. Pali used the tendon sheath actuation on robotic finger and managed to using the friction model to control the joint force[13]. S. Phee proposed a new method by using the friction model and calibration to estimate the output force and the elongation[14]. T. N. Do applied the tendon sheath actuation for surgical systems by using a nonlinear control model[15].

Although there are many researches on the tendon sheath actuation, it still has some problems unsolved. Generally, it assumed that the tendon and the hollow coil wire have the same radius, however, the tendon radius is actually smaller than the coil’s. So the different tendons and sheath radiiuses may cause different friction. Another unconsidered factor is the tendon pulling velocity which may cause the different friction. The sheath wire shape is fixed in these researches, but usually it will be changed in the actuation. So the differences of the sheath shape also should be considered.

In order to find out the force propagation between the input and the output force in the tendon sheath actuation system, a friction model is proposed and a series of experiments have been carried out. Firstly, the force propagation of tendon sheath actuation was tested under different pull velocities. Secondly, it was tested in various tendons which have different radius. At last, it was tested with different curvatures for the sheath. In order to explain how these factors affect the friction, a modified friction model is then presented.

II. FORCE PROPAGATION MODELING

A. The Friction Model of Tendon and Sheath

According to [10] and [14], the classical friction model of tendon and sheath can be described as Fig. 1. It assumed the sheath to be bend with a constant radius, and the friction coefficient \( \mu \) between the sheath and the tendon is also constant. For a little arc with a unit length \( dx \) shown in Fig. 1, the arc angle is \( dx \), \( R \) is the bend radius. \( T \) is the tendon force in the proximal end of the arc. \( dT \) is the increased tendon force for the distal end of the arc. \( N \) is the normal force that the tendon is exerting on the sheath in this unit length and \( F_f \) is the friction between the tendon and the
sheath in this unit. So applying the force balances on this unit arc we can obtain that:

\[
\begin{align*}
\frac{d\alpha}{dx} &= \frac{d\alpha}{R} \\
T \frac{d\alpha}{N} &= \mu N \\
F_i &= dT \\
F_f &= \mu N
\end{align*}
\]

(1)

If we assumed that the dynamic friction coefficient is the same as static when the tendon is moving, when the tendon is pulled to move, (1) can be transformed as:

\[
\frac{dT}{T} = \mu \frac{dx}{R}
\]

(2)

In(2), \(T_0\) is the initial tendon force and \(x\) is the arc length along the move direction.

Until now, it is assumed the tendon sheath actuation has a constant radius along with the whole length. But actually, the sheaths are free to move in the actuation and will have different curvatures along the whole length. In order to solve this problem, the sheath can be divided into \(n\) sections. In every section, the curvature can be assumed as a constant \(iR\), as shown in Fig. 2. Then the tendon force along the sheath can be written as follow:

\[
T_i = T_0 e^{-\mu \frac{x}{R}} (x_{i-1} < x < x_i)
\]

(3)

While \(x_i\) is the length from proximal end to the section \(i\). \(T_i\) is the tendon output at the length \(x\) point. Along the whole length of the sheath we can get:

\[
T_d = T_p e^{-\mu \frac{x}{R}}
\]

(4)

In(4), \(T_p\) is the proximal end input force, \(T_d\) is the distal end output force. \(x_o\) is the whole length. If we set

\[
q = \mu \frac{x}{R} + \mu \frac{x-x_1}{R} + \cdots + \mu \frac{x-x_{i-1}}{R}
\]

Which is only about the shape of the sheath, equation (4) can be simplified as:

\[
T_p = T_p e^{-\mu x}\]

(5)

B. Analysis of Influencing Factors on Friction

For a tendon sheath system, the force propagation of the output force \(T_d\) and the input force \(T_p\) is the most important feature that should be concerned. The friction is the main factor that affects the output force. For the whole sheath, it can be simply written as:

\[
T_d = T_p - F_f
\]

(6)

Using (5) and (6) we can get:

\[
F_f = T_i (e^\mu - 1)
\]

(7)

From(7), it can be known that the friction \(F_f\) is related to the shape of the sheath \(q\) and the distal load \(T_p\). But for a tendon sheath actuation system, there are some other factors such as the tendon diameter, the sheath inside diameter, and the tendon pulling velocity and so on. These factors may also affect the friction, but the friction model doesn’t consider it. So it needs to carry out some experiments to find out the relationship between these factors and the friction.

III. EXPERIMENTS

In order to figure out how the factors affect tendon sheath actuation system, a series of experiments have been carried out. These factors are distal load, the tendon diameter, the sheath inside diameter, the tendon pulling velocity and the curvature of the sheath. For changing the tendon diameter and the sheath inside diameter have the same effect for our experiment, so we only changed the tendon diameter. The distal load \(T_d\) and the pulling force \(T_p\) is the key point, so the basic test method is to record the \(T_d\) in various distal loads. The basic experiment set-up is shown in Fig. 3, it contains a linear motor (HIWIN LMCB5, China), a force sensor (FUTEK LSB200, American), a set of weights and a sheath with inner diameter 0.7mm and outside diameter 1.2mm. The distal load can be changed by using different weights hanged at the distal end. For each moving, the linear motor pulls the proximal end of the tendon moving 30cm by the force sensor in a uniform velocity. When the linear motor achieved the target velocity, the force sensor...
start to recording the pulling force until the linear motor arrived at 25cm. Then the linear motor slow down and return to initial position. Under the basic experiment set-up, combining with other factors, we can get three different conditions:

- Testing the $T_p$ using one tendon diameter at a fixed shape and different velocities in different loads
- Testing the $T_p$ using different tendon diameters at a fixed shape and the same velocity in different loads
- Testing the $T_p$ using one tendon diameter at different curvatures and the same velocity in different loads

According to the three different conditions, the experiment can be carried out in three parts as following:

A. Velocity Change Experiment

In this experiment part, the sheath was fixed at a random shape and keeping unchanged, as shown in Fig. 3. The tendon diameter is fixed to 0.54mm. The pulling velocities are various from 5mm/s, 10mm/s, 15mm/s to 20mm/s. The distal load are various from 0g, 10g, 20g, 50g, 100g to 200g. For every test, the distal load was firstly fixed to a certain weight, and the linear motor velocity was changed in order and then the distal load was changed.

B. Tendon Diameter Change Experiment

In this experiment part, the sheath was fixed at a random shape and keeping unchanged as previous. The linear motor velocity is fixed to 10mm/s. The tendon diameters are various form 0.24mm, 0.30mm, 0.36mm to 0.54mm. The distal load are various from 0g, 10g, 20g, 50g, 100g to 200g. For every test, the distal load was firstly fixed to a certain diameter, and the tendon diameter was changed in order and then the tendon diameter was changed.

C. Curvatures Change Experiment

In this experiment part, the linear motor velocity is fixed to 10mm/s. The tendons diameters are 0.54mm. The distal load are various from 0g, 10g, 20g, 50g, 100g to 200g. The sheath was wound one cycle on a cylinder and the rest of the sheath is fixed in a linear shape, as show in Fig. 4. The cylinder can be changed in different diameters at 82mm, 96mm, 112mm and 136mm. For every test, the sheath was firstly fixed to a certain cylinder, and the distal load was changed in order and then the cylinder was changed.

IV. RESULT AND ANALYSIS

We observe the tendon force with 1 KHz sampling frequency for each load applied, and calculate the mean value of the tendon force $T_p$ in 24 seconds period. The experiment results are shown as follow:

A. Different Velocities for the $T_p$

The result of different velocities for the $T_p$ is shown in the Fig. 5. From the figure, we can find out that for a certain distal load, the $T_p$ is changed very little as the pulling velocities changed. But when distal load is heavy, the $T_p$ is changing around the mean value as the velocity increasing.
B. Different Tendon Diameters for the $T_p$

The result of different tendon diameters for the $T_p$ is shown in the Fig. 6. The Fig. 6 (a) shows the $T_p$ with the distal load changing grouped by the tendon diameters. It can be found that for a certain tendon, the $T_p$ is increased as the distal load increasing. Using the least square method to fit $T_p$ and $T_d$, the max error for the tendon diameters of 0.24mm, 0.30mm, 0.36mm and 0.54mm is 0.055N, 0.066N, 0.134N and 0.191N. It indicates that the small diameters have a very good linearity and the large diameters’ are a little bad. The Fig. 6(b) shows the $T_p$ with the tendon diameters changing grouped by the distal load. It can be found that as the diameter increasing, the $T_p$ is increased, especially when the distal load is heavy. The linear relationship for the $T_p$ and the diameters are not good. The max mean error is 0.61N when the diameter is 0.35mm and the distal load is 200g.

C. Different Curvatures for the $T_p$

The result of different curvatures for the $T_p$ is shown in the Fig. 7. It can be found that as the curvatures increasing, the $T_p$ is decreased. The curvatures and the $T_p$ have no linear relationship.

D. Analysis on the Tendon Sheath’s Parameter Determination

From the result of the experiment, we can found there are several factors such as the tendon pulling velocity, tendon diameter, the sheath curvature that can affect the friction for a tendon sheath action. But from (7) we can find that the friction is only about the shape of the sheath and the distal load. So there may be some other factors that we didn’t considered in(7). Through the three experiment parts, when the pulling force is over 10N, the sheath may buckle as shown in Fig. 8. This changes the shape of the sheath and the parameter $q$ may changes. This will make the $T_p$ get a larger error than that of
the pulling force under 10N.

For the different velocities, equation (7) shows it has no relationship with the pulling velocity. But the experiment shown that the $T_p$ is changed as the velocities changing by a heavy load. As the $T_p$ is a random variation around the average value. So the sheath buckling may be the mainly reason for $T_p$ changing.

For the different tendon diameters, the friction model doesn’t consider it. But for a single tendon, when the shape of the sheath was determined, the parameter $q$ is fixed. So (5) can be simply write as:

$$T_p = T_s e^q = T_s \cdot K$$  \hspace{1cm} (8)

It can predict that the pulling force $T_p$ is proportional to the distal load $T_s$ when the sheath shape is fixed. In the experiment results, for every single tendon, the pulling force $T_p$ can be fitted to a linear function of the distal load $T_s$ with few errors. (The sheath buckling is also the reason for the bigger error in heavy load tests), which is consistent with the predicted model.

When the result of experiment part two grouped by load, it shows that the $T_p$ is increased by the diameter increasing. This cannot simply be attributed to the changes of the sheath buckling. Because all the $T_p$ are changed as the load changing, not only for $T_p$ over 10N, and the pull forces are increasing step by step, not a random changing around the average value. So there may be some other factors which affect the result.

The friction model mentioned in part II assume that the tendon and the sheath is only a point contact at point A in Fig. 1. So the normal force $N$ is just straight up and $F_f = \mu N$. But in fact, when there is a normal force between tendon and sheath, the sheath coil will deform and the contact area changes to an arc BC, as shown in Fig.9 (a). The normal force is distributed over the arc and the direction is not just straight up. The arc BC can be divided into two symmetrical parts at the point A and the normal force over the arc AB can be merged as force $N_f$ as shown in Fig.10 (a). $\theta$ is the angle between $N_f$ and $N$. So (1) should be changed as:

$$d\alpha = \frac{dx}{R}$$
$$T d\alpha = N$$
$$F_f = dT$$
$$N = 2N_f \cos \theta$$
$$F_f = 2\mu N_f$$

Then we can get:

$$T_p = T_s e^{-\mu \theta \cos \theta}$$ \hspace{1cm} (10)

For different tendon diameters, the angle $\theta$ will be increased as the diameter increasing ($\theta_1 < \theta_2$), as shown in Fig.9 (b). From (10) it can be known that as the $\theta$ increasing, the pulling force $T_p$ will be increased, which is corresponding with the experiment. Then we apply (10) into (5), and translate it as fellow:

$$\frac{1}{\cos \theta} = -\ln \frac{T_p}{T_s} / q$$ \hspace{1cm} (11)

$\frac{T_s}{T_p}$ is the linear fit coefficient can be get from experiments. For the fixed shape of sheath, q is a constant, but we can’t get it. So $\theta$ can’t be calculated out directly. In order to found out the how the tendon diameter effect the friction. We use the ratio of the tendon diameter $D_t$ referring to sheath diameter $D_s$ (named $\eta$) as X axis, $-\ln \frac{T_s}{T_p}$ as Y axis for each tendon draw a figure as Fig. 10. We tried to fit them into a line. In
order to make the fit more sensible, we add another two tendon experiments with diameters 0.40mm and 0.45mm. At first, we fit them with linear fit and the RMSE is 0.0438. R-square is 0.9621. Then we used the cubic fit. The RMSE is 0.02791 and the R-square is 0.992. The quality of cubic fitting is better than that of linear fitting, but the cubic fitting is more complex than linear fitting. The cubic fitting shows that when the ratio $\eta$ between 40% and 65%, the actuation force changes greatly than that of outside.

From the experiment results, it can be known that if we want a small friction for our system, we should choose a small tendon or a big sheath and the sheath curvature should be kept the straighter the better. But if chosen a small tendon, the distal load is limited and if chosen a big sheath, the more space is needed. So there should be a tradeoff between the friction and the tendon or sheath size. From the cubic fitting of diameter and tendon force, it can be known that if $\eta$ is between 40% and 65%, we can using a smaller tendon with larger friction decreasing.

**V. CONCLUSION**

In this paper, a friction model is presented to find out the force propagation between the input and the output force in the tendon sheath actuation system. To verify the correctness of the model, a series of experiments have been carried out. Some other factors like the pulling velocity and the tendon diameter of the sheath which are not considered in the previous friction model are also tested in the experiments. The experiment results show that the pulling velocity almost doesn’t affect friction. For the curvature of the sheath, the smaller curvature is, the bigger the friction is. For different tendons, the greater difference between the tendon and sheath size is, the smaller the friction is. In order to find the influence of tendon diameter on the actuation force, a modified model is presented. The cubic fitting is applied to describe the relationship between the tendon's diameter and actuation force. It indicate, when the ratio of tendon diameter referring to sheath inner diameter lies between 40% and 65%, the actuation force changes greatly than that of outside. When the friction is to be reduced by decreasing the tendon diameter or increasing the sheath inner diameter, better performance will be obtained in this range.

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