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Highlights

- > Dynamic friction model for tendon-sheath system is developed and proposed.
- > An experimental setup to validate the model is designed and built.
- > Model-parameter identification is carried out on the test setup.
- > The hysteresis behaviour on the pulled/released phase is well captured.
- > The friction in sliding/pre-sliding regimes with smooth transitions is well modelled.

A New Approach of Friction Model for Tendon-Sheath Actuated Surgical Systems: Nonlinear Modelling and Parameter Identification

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ABSTRACT

Nonlinear friction in tendon-sheath mechanism (TSM) introduces difficulties in predicting the end-effector force inside the human body during surgical procedures. This brings a critical challenge for surgical robots that need high fidelity in haptic devices. This paper presents a new friction model for a TSM in surgical robots. The model considers the TSM as an element disregarding the tendon sheath curvature and permits an arbitrary configuration of sheath. It allows for the accurate modelling of friction force at both sliding and presliding regimes. Unlike existing approaches in the literature, the model employs not only velocity but also acceleration information. It is also able to capture separate hysteresis branches in the large displacement using a unique differential equation. Transition between the two regimes is smooth. To validate the approach, an experimental setup is developed to measure the tensions at both ends of the TSM. The model parameters are identified and experimentally validated using an optimization method and different types of input signals. It assures an accurate prediction of nonlinear hysteresis behaviour of TSM, especially at near zero velocities. This model can be used to provide an estimate of the friction force in a haptic feedback device to the surgeons.

Index terms: nonlinear friction, tendon sheath, sliding regime, presliding regime, identification, haptic feedback.

1. INTRODUCTION

Natural Orifice Transluminal Endoscopic Surgery (NOTES) has received much attention in the surgical communities during the past few years. It has overcome many drawbacks in open surgical procedures such as no abdominal incisions, better cosmetic and faster recovery for patients [1-3]. The size and dexterities of surgical tools have become more demanding, making them suitable for more complex tasks in surgical operations such as suturing or cutting. In such cases, tendon-sheath mechanism (TSM) is preferred because it can pass through a long narrow and tortuous path, and allows for operating in small working areas because of a drastic reduction in the system size [4, 5]. However, nonlinear friction in such mechanism causes major challenges in enhancing system performances. In NOTES system, it is nearly impossible to integrate sensors at the tool tips because of their size and issues of sterilization. On the other hand, it was reported that haptic feedback to the surgeon will be essential for safe surgery [6-8]. Without haptic feedback, surgeons cannot have the same feel as they have in direct touch on the tissues. Since sensors are not available at the tool tips, by

means of an accurate transmission model of flexible TSM described in this paper, we can accurately estimate the force at the tool tip of a surgical device used inside the human's body.

Various analytical model parameters of friction and transmission for the TSM using lumped mass model combined with Coulomb friction model are available in literatures. Kaneko *et al.* [9-11] provided a discrete lumped mass model using Coulomb friction model. Palli *et al.* [12, 13], Sun *et al.* [14], and Low *et al.* [15] modelled the transmission for the TSM under the assumption of the same pretension for small elements. Do *et al.* [16, 17] proposed compensation control for position. However, no force transmission schemes have been introduced so far. Agrawal *et al.* [18, 19] used a set of partial differential equations to model a single TSM and a pair of TSM in a closed loop approach. These existing approaches only consider the transmission model for the TSM when the configuration is known. They assumed constant pretension for the whole tendon elements and sheath curvatures for their model approaches. The model becomes more complex when more elements are considered. In addition, these are limited in the prediction of friction force when the system operates near zero velocity (small displacement or stationary state) and the models lack a smooth transition from small displacement to large displacement.

Hysteresis nonlinearities for mechanical systems have been studied and discussed in the literature [20, 21]. Several models for dynamic friction have been proposed and explored [22-30]. Some authors modelled the presliding regime based on the material property such as elastic-plastic contacts between two surfaces [31-33]. The others used the velocity and acceleration information to capture the separate hysteresis branches in the sliding regime [34-37]. Although Do *et al.* [38] modelled the friction transmission for a single TSM but still limited in a high number of model parameters as well as offset point problems when the system operated from small to large displacement. The friction phenomena of the TSM possess complex nonlinearities in the acceleration and deceleration directions. Although the friction characteristics of the hydraulic cylinder in the fluid lubrication regime possesses asymmetric hysteresis profile in the acceleration and deceleration directions, there is a major difference between tendon-sheath friction force and the hydraulic friction in a cylinder [39-41]. As described in our previous work [38], the tendon-sheath friction profile is asymmetric for both positive and negative directions. However, the friction behaviours in both positive and negative acceleration direction are completely different. In the positive velocity, the tendon-sheath friction force increases in the positive acceleration but decreases in the negative acceleration direction (see Fig. 1(b)). In contrast, the friction force of the hydraulic cylinder increases with the increase of velocity for both positive and negative acceleration directions. In addition, the nonlinear profile of the tendon-sheath friction not only depends on the tendon pretension but also depends on the tendon-sheath configuration while the cylinder friction is affected by the packing material and the pressures in the cylinder chambers. Among these models, the LuGre model [29] has been one of the most widely used. The LuGre model is able to describe a wide class of friction characteristics such as sliding, presliding, varying break-away force due to its simple structure, inspite the lack in computing the friction behaviours (non-local memory) in the presliding regime. Hence, in order to overcome these shortcomings, the Leuven model [27], the Elasto-Plastic model [26], and the GMS [28] have been proposed. For the TSM, the friction behaviour is rather complex. The forces are different when the motion is accelerating and decelerating. Unfortunately, in the sliding regime, all the aforementioned models cannot simulate the friction characteristics of a TSM.

Instead of using a lumped mass model or an elegant discretized model, this paper presents a new dynamic friction model for tension transmission of the tendon sheath based on a unique tendon sheath element in any sheath configurations. For some surgical applications utilizing TSM where micrometre accuracy is not of utmost importance, non-local memory hysteresis in the presliding regime is not

critical to model. Therefore, based on the friction characteristics of a TSM, a new dynamic friction model is developed by modifying the LuGre friction model. In the sliding regime, the friction force is characterized by a set of velocity and acceleration dependent functions. For the presliding regime, the friction force is described by the average bristle deflection with an offset point. In addition, the friction characteristics of TSM are experimentally examined using a suitable setup. An efficient identification method is also applied to generate the model parameters. The proposed model can account for various effects of nonlinear hysteresis for both loading and unloading phases of tendon-sheath motion under arbitrary configuration of the sheath shapes and excitations.

This paper is organized as follows. In section 2, the tension transmission characteristics of TSM are discussed. Section 3 presents the proposed friction model to capture the nonlinear properties of TSM. Section 4 introduces a suitable experimental setup and results for a tendon sheath under various input signals. The parameter identification is carried out in section 5. The comparisons between the proposed model and experimental data are drawn in section 6. Finally, the discussion and conclusion part is given in section 7.

2. Tension Transmission and Friction Characteristics in the TSM

Fig. 1(a) illustrates the structure of a tendon-sheath mechanism (TSM) used in the NOTES system. To investigate the friction characteristics of a tendon inside a sheath, a single TSM is used. Let T_{in} and T_{out} denote the tensions at the proximal end and distal end of the TSM, x_{in} denotes the displacement at the proximal end. The friction force between the tendon and the sheath is expressed by:

$$F = T_{in} - T_{out} \quad (1)$$

For the tendon sheath system, in order to avoid the tendon slack, a pretension is applied to the tendon at initial stage. The dynamic characteristics of the tendon-sheath friction are shown in Fig. 1(b), in which the left panel of the figure presents the relation between the friction force and the relative velocity of the proximal end while the right panel shows the relation between the friction force and the displacement of the proximal end. Suppose that the tendon initially moves towards the distal end. When the tendon reverses its direction, the friction force between the tendon and the sheath prevents the immediate transmission of both motion and tension from proximal end to distal end: the motion at the proximal end cannot immediately propagate to the distal end, which does not yet move (points A to B in the left panel of Fig. 1(b)). As the tension T_{in} increases further, at point B, the tendon at the distal end begins to move: motion has been transmitted (points B to D in the left panel of Fig. 1(b)). When motion at the proximal end changes its direction, a level of friction still exists between the tendon and the sheath. Hence, the distal end cannot immediately reverse its motion together with the proximal end (points D to E in the left panel of Fig. 1(b)). Until the friction force and the tension T_{in} decreases further, the tendon at the distal end begins to move: motion has been reversed (points E to A in the left panel of Fig. 1(b)).

3. Modelling of Dynamic Friction Force in TSM

In this section, we present a new approach of the nonlinear friction model in the TSM. Unlike current approaches in literatures, the proposed model structure is independent to the sheath configuration; it allows for arbitrary configurations of the TSM with any complex shapes. In addition, it is able to capture the friction force at near zero velocities using smooth functions. It is known that the LuGre

model [29] has a simple structure and it is able to capture a wide range of friction force for both the sliding and presliding regimes. In the sliding regime, the LuGre model, which possesses a Stribeck curve, has similar characteristics as current friction models like the Leuven or Elasto-Plastic model. However, this Stribeck curve cannot represent the friction force in the sliding regime of TSM. Therefore, based on the friction characteristics of the TSM, a new dynamic friction model is developed by modifying the LuGre model and its structure. To model the nonlinear friction, some assumptions are needed: the tendon is at some suitable pretension in order to avoid the tendon slack; accumulated curve angles of the TSM are unchanged.

3.1. A Short Review on the LuGre Model

The main drawback of static friction models is a discontinuous phenomenon when the system operates with small displacements. This is due to the use of a signum function for velocity in classical friction models such as Coulomb, Viscous, Stribeck or switching models [42]. To deal with this shortcoming, the LuGre model, which appears as a generalization of the Dahl model, is preferred. This model not only considers the presliding regime phenomena (small displacement) but also takes into account the Stribeck effect in the sliding regime (large displacement) [29]. The basis of the LuGre model is illustrated in Fig. 2.

Stiction is considered as the average force applied by elastic springs under tangential microscopic displacement. The two surfaces make contacts at various asperities (represented by bristles). Bristles deflect as springs whenever there is a relative velocity between the two surfaces. This deflection results in the friction force. However, if the deflection is sufficiently high, then the bristles will slip. The LuGre model can be expressed in term of the velocity and average bristle deflection which is modelled by a first order differential equation:

$$\dot{\zeta} = \dot{x} - \frac{|\dot{x}| \zeta}{S(\dot{x})} \quad (2)$$

where $\dot{x}$ is relative velocity between the two surfaces, ζ is average deflection of bristles (internal state), $S(\dot{x})$ is the Stribeck function that specifies how the average deflection of bristles depend on the velocity. One of possible form for the function $S(\dot{x})$, which is introduced in Canudas de Wit [29], is expressed by:

$$S(\dot{x}) = \frac{1}{\sigma_0} (F_c + (F_s - F_c) e^{-(\dot{x}/\dot{x}_s)^2}) \quad (3)$$

Where F_c is the Coulomb friction level, F_s the level of stiction force, $\dot{x}_s$ is the Stribeck velocity. Finally, the LuGre friction model is expressed by:

$$F = \sigma_0 \zeta + \sigma_1 \dot{\zeta} + \sigma_2 \dot{x} \quad (4)$$

where σ_0 is the stiffness, σ_1 is damping coefficient, σ_2 is the viscous friction coefficient.

3.2. Shortcoming of the LuGre Model for Large Displacement.

Dynamic friction nonlinearity is modelled using LuGre model approach given by Eq. (2) to Eq. (4). The experimental data, which are collected from the experimental set up (discussed later in section 4), are used for identification and comparison. Six model parameters are simultaneously optimized using

Genetic Algorithm (GA-given in section 4). The optimized parameters are: $\sigma_0 = 58.574$, $\sigma_1 = 0.841$, $\sigma_2 = 0.872$, $F_c = 4$, $F_s = 5.94$, $\dot{x}_s = 0.66$. Fig. 3 shows the identification results as well as a comparison between the LuGre model and experimental data. The LuGre model is able to capture the friction force for small displacement (the presliding regime). However, it is not able to model the characteristics of the nonlinear friction force of the TSM for large displacement (the sliding regime). There is a large error between the LuGre model and the measured tendon-sheath friction: Expressed in mean square error (MSE, equal to 1.4538 (*MSE*)). It comes from the fact that the Stribeck curve in the sliding regime given by Eq. (3) is not able to capture the separate curves during the acceleration and deceleration phase. These separate curves can be observed from the left panel of Fig. 1(b). To model such separate curves, a new acceleration and velocity dependent function will be introduced. This approach will be presented in the next section.

3.3. Dynamic Modelling of Tendon-Sheath Friction in the sliding and presliding regimes

It is known that the friction properties between the tendon and the sheath are asymmetric for both positive and negative velocity. In the sliding regime, the friction force is different for acceleration and deceleration (see the left panel of Fig. 1(b)). In addition, near zero velocity, there is an offset point on the hysteresis curves when the friction force changes from small displacement to large displacement as well as in acceleration and deceleration directions. The LuGre and other models are not able to capture the nonlinear friction of the TSM in the large displacement (the sliding regime-see the left panel of Fig. 1(b)). Therefore, to capture the asymmetric characteristics, our approach is to modify the LuGre model. In this paper, two major modifications to the LuGre model are carried out. The first is to modify the velocity variable in Eq. (2) to be a function of the offset point λ and the acceleration $\ddot{x}$, i.e. $\dot{x} \rightarrow (\dot{x} + \lambda \text{sign}(\ddot{x}))$. The second is to modify the term $\frac{\zeta}{S(\dot{x})}$, which contains the Stribeck curve

$S(\dot{x})$, to include the function of velocity, internal state, and acceleration, i.e. $\frac{\zeta}{S(\dot{x})} \rightarrow \frac{\zeta}{S_{new}(\dot{x}, \ddot{x})} \left| \frac{\zeta}{S_{new}(\dot{x}, \ddot{x})} \right|$. Then Eq. (2) is replaced by:

$$\dot{\zeta} = \rho \left((\dot{x} + \lambda \text{sign}(\ddot{x})) - \frac{|\dot{x} + \lambda \text{sign}(\ddot{x})| \zeta}{S_{new}(\dot{x}, \ddot{x})} \left| \frac{\zeta}{S_{new}(\dot{x}, \ddot{x})} \right| \right) \quad (5)$$

where λ is the offset point of the adjustment; ρ is a scaling factor, $S_{new}(x, \dot{x})$ is the new function that control the separate curves in the sliding regime, $x = x_{in}$ is the displacement at the proximal end of the TSM, the dot at the top of variables represents for the first order derivative with respect to time,

$$\text{sign}(\bullet) \text{ is the signum function that is defined by } \text{sign}(\bullet) = \begin{cases} 1 & \text{if } (\bullet) > 0 \\ 0 & \text{if } (\bullet) = 0 \\ -1 & \text{if } (\bullet) < 0 \end{cases} .$$

The modified function $S_{new}(x, \dot{x})$, which controls the hysteresis asymmetric loops with large displacement for negative and positive velocity, is expressed as follow:

$$S_{new}(x, \dot{x}) = \begin{cases} S_{+v1} & \text{if } \dot{x} \geq 0, \ddot{x} \geq 0 \\ S_{+v2} & \text{if } \dot{x} \geq 0, \ddot{x} \leq 0 \\ S_{-v} & \text{if } \dot{x} \leq 0 \end{cases} \quad (6)$$

where

$$S_{+v1} = \rho_1 + \mu_1 e^{-f_1(\dot{x}, \ddot{x})} \text{ with } f_1(\dot{x}, \ddot{x}) = \frac{\kappa_1 |\dot{x}|}{|\kappa_2 \ddot{x}| + 1} \quad (7)$$

$$S_{+v2} = \rho_1 + \mu_1 e^{-f_1(\dot{x}, \ddot{x})} + \mu_2 \left(1 - e^{-|\kappa_3 \ddot{x}|}\right) \quad (8)$$

$$S_{-v} = \rho_2 + \text{sign}(\ddot{x}) \mu_3 e^{-f_2(\dot{x}, \ddot{x})} = \begin{cases} S_{-v1} & \text{if } \dot{x} \leq 0, \ddot{x} < 0 \\ S_{-v0} & \text{if } \dot{x} \leq 0, \ddot{x} = 0 \\ S_{-v2} & \text{if } \dot{x} \leq 0, \ddot{x} > 0 \end{cases} \quad (9)$$

The function S_{-v} contains three sub-functions, which are expressed by:

$$S_{-v1} = \rho_2 + \mu_3 e^{-f_2(\dot{x}, \ddot{x})} \text{ with } f_2(\dot{x}, \ddot{x}) = \frac{\kappa_4 |\dot{x}|}{|\ddot{x}| + \kappa_5} \quad (10)$$

$$S_{-v2} = \rho_2 - \mu_3 e^{-f_2(\dot{x}, \ddot{x})} \quad (11)$$

$$S_{-v0} = \rho_2 \quad (12)$$

where $f_1(\dot{x}, \ddot{x})$, $f_2(\dot{x}, \ddot{x})$ are velocity and acceleration dependent functions; ρ_i, μ_j, κ_l ($i=1,2$; $j=1,\dots,3$; $l=1,\dots,5$) are coefficients that control the shape of hysteresis loops in acceleration and deceleration direction.

To illustrate for the capability of the model approach, one of the sliding functions (Eq. 7 and Eq. 8) in positive velocity is considered and illustrated in Fig. 4.

At the reversal point, there exists a special characteristic for the sliding functions S_{+v1} , S_{+v2} , S_{-v1} , S_{-v2} . The values of each of sliding functions for positive velocity or negative velocity are the same (see Fig. 4). For positive velocity, for the whole motions when acceleration approaches zero value, S_{+v1} and S_{+v2} will become a velocity dependent function, that is $S_{+v1, \text{ at } \ddot{x}=0} = S_{+v2, \text{ at } \ddot{x}=0} = \rho_1 + \mu_1 e^{-f_1(\dot{x}, \ddot{x}=0)}$. Similar argument for negative velocity with sliding functions S_{-v1} and S_{-v2} . At zero acceleration, these functions become $S_{-v1, \text{ at } \ddot{x}=0} = S_{-v2, \text{ at } \ddot{x}=0} = S_{-v0} = \rho_2 + \mu_3 e^{-\kappa_4 |\dot{x}|}$. This property shows that the proposed model is able to capture the separate hysteresis loops for acceleration and deceleration direction as well as to guarantee a smooth transition between the two functions, i.e. S_{+v1} and S_{+v2} ; S_{-v1} , S_{-v2} . The simulation of the sliding functions in positive velocity for this property is presented in Fig. 4. The signal used is $\dot{x} = 18.75 \cos(3.75t - 1.56)$ with and the optimized parameters are: $\rho_1 = 8.855$, $\mu_1 = -6.533$, $\kappa_1 = -0.341$, $\kappa_2 = 0.078$, $\kappa_3 = 0.0063$, $\mu_2 = 14.6$.

The viscous friction $\sigma_2 \dot{x}$ in the original LuGre model is explicitly eliminated in the proposed model structure as the function $S_{new}(\dot{x}, \ddot{x})$ contains the slopes of hysteresis loops. The damping coefficient σ_1 in the original model is also eliminated in order to reduce the model parameters. This elimination does not affect the capability of the model approach. Finally, the proposed friction model in TSM can be expressed by:

$$F = \sigma_0 \zeta \quad (13)$$

where ζ is a solution of Eq. (5). By combining the sliding and presliding regimes (as given in Eq. (5) to Eq. (13)), the proposed friction model can capture various hysteresis phenomena in TSM with any amplitudes and frequencies from the input side. The transition between the two regimes as well as the sliding functions at acceleration reversal points is also smooth. In addition, the proposed model can adapt to any tendon-sheath shapes since the model structure is independent of configuration. The validation will be presented in the next section.

4. Experimental Work and Identification Method

This section presents the experimental set up and identification algorithm for the model parameters. A schematic set up is established to investigate the nonlinear characteristics of friction in the TSM. An efficient identification method (Genetic Algorithm) is applied to generate the optimal model parameters.

4.1. Experimental setup

To investigate the friction force characteristics between the tendon and the sheath, a dedicated experimental setup has been established as shown in Fig. 5. The TSM, from Asahi Intecc Co., of 1.2m length is used. It consists of a round-wire coil sheath (an outer diameter of 0.8mm and inner diameter of 0.36mm) and a Teflon coated wire tendon (WR7x7D0.27mm in specification). To measure the tensions at two ends of the TSM, two load cells LW-1020-50 from Interface Corporation are used. One is connected to the proximal end to measure the tension input T_{in} while the other is attached to the distal end to measure the tension output T_{out} . Two linear sliders are used to hold the two load cells. Motion is provided by a Faulhaber 2642W024CR DC servomotor which is connected to a pulley (pulley input) at the proximal end. This motor is driven by ADVANCED motion controls 25A8PWM servo drive. In order to maintain the motion for both loading and unloading phases, a spring is used at the distal end. A high-resolution encoder E6D-CWZ1E 3600P/R 0.5M from Omron, placed at proximal end, is used to provide motion information of the tendon.

During the experiment, a pretension force is applied to the tendon to prevent it from slacking and the total curve angles of the sheath configuration are maintained. The encoder output is directly connected to a dSPACE DS1104 controller system while each of the two load cells is connected to the dSPACE DS1104 via a DCA compatible signal conditioner from Interface. The signals and the identification are managed by software in the MATLAB Simulink environment. When the tendon is pulled at the input side by the DC motor, the tension in the tendon will increase in response to resistance force of the spring as it is transmitted to the output side. When the DC motor reverses its direction again, due to resistance force of the spring, the tendon is pulled back towards the distal end. Using the tension values from load cells at the two ends, the friction force between the tendon and the sheath can be calculated (see Eq. (1)).

4.2. Identification method

The identification procedure consists of estimating the unknown model parameters using the Genetic Algorithm (GA), which is a stochastic optimization method that is based on the concepts of natural selection and genetics, and the Nelder-Mead Simplex method [43-45]. The GA is used to create an initial guess of model parameters. It employs natural evolution to move from one population of “chromosomes” to a new population where unfit components are eliminated. The GA generates the next generation sets using operators and evaluates the future chromosomes based on a fitness function. This fitness function will be used as a stop condition. For the optimal values of the

parameters, the value of fitness function should be converted to a minimum value. In this case, we use the mean square error (MSE) as a representative of the fitness measurement, which is defined by:

$$MSE(\hat{F}) = \frac{1}{N} \sum_{i=1}^N (F_i - \hat{F}_i)^2 \quad (14)$$

where F is the friction force values which are measured from the experiment, i is sampling index, N is number of samples from experimental data, and $\hat{F}$ is the estimated values from the proposed friction model.

The Nelder-Mead Simplex, which is a direct search method that can be utilized to predict the best solution of the model parameters, is subsequently applied to refine the initially identified results. These were done using MATLAB identification toolbox and the command *fminsearch*. The relative velocity is obtained from numerical differentiation of the measured displacement from the encoder. The experimental data are filtered using zero-phase digital filtering with *filtfilt* command in MATLAB environment.

5. Identification Results and Validation

In the experiment, two types of motion excitations are provided using the DC servomotor: a single periodic motion and a non-periodic input motion comprising a sum of two signals. The friction force between the tendon and the sheath is calculated from Eq. (1) using the measured input tension T_{in} and the measured output tension T_{out} . A common feature of dynamic friction of the TSM observed from experimental results is the asymmetric hysteresis loops in positive and negative velocity direction. These nonlinear properties will be analysed at the sliding and presliding regimes.

The parameters, given in section 3.3, have been identified using Genetic Algorithm and Nelder-Mead Simplex method as in section 4.2. The inputs used are (a) a periodic motion with frequency of 0.2 Hz and amplitude of 1 rad; and (b) a non-periodic motion made up of the two signals (the first one has an amplitude 0.5 rad and frequency of 0.2 Hz and the second one has an amplitude of 0.6 rad and frequency of $0.25\sqrt{3}$ Hz). For the friction model, which is given by Eq. (5) to Eq. (13), model parameters have been optimized, i.e. $\rho_1 = 2.8642$, $\mu_1 = -1.772$, $\kappa_1 = 0.084$, $\kappa_2 = 0.4104$, $\mu_2 = 0.342$, $\kappa_3 = 9.345$, $\rho_2 = 0.072$, $\mu_3 = 0.9991$, $\kappa_4 = 0.1704$, $\kappa_5 = 1.1823$, $\lambda = 0.156$, $\rho = 7.938$, $\sigma_0 = 5.038$. The identification and comparison results are shown in Fig. 6. The time history of the applied input signal is given in Fig. 6(a) while the comparison between the proposed model and experimental data is presented in Fig. 6(b). To evaluate the effectiveness of the proposed model, the error between the model and experimental data is also shown in Fig. 6(c). It has a peak-to-peak of 1N in the error. For easy observation and evaluation, the mean square error (MSE), i.e. $MSE=0.027$, for this comparison is also given. Since the hysteresis curves in the sliding regime (the large displacement) are distinguished, it can be observed that the friction force is well captured by the proposed model for positive and negative velocity. In addition, in the small displacement region (the presliding regime), the proposed model is smooth. These properties can be observed from Fig. 6(d) and Fig. 6(e) (friction in relation with velocity and displacement). The ultimate goal of the approach is to provide the force information (tension output- T_{out}) to haptic device and subsequently to a surgeon. Hence, the output tension is directly estimated basing on the input tension T_{in} using the proposed friction model and without using any internal sensor at distal end of the TSM. This result can be observed from Fig. 6(f), in which a good correlation between the measured output tension and its estimated values can be seen.

From these figures and the mean square error, it can be concluded that the proposed model ($MSE=0.027$) gives a better prediction of the friction force than the LuGre model ($MSE=1.4538$, given in sections 3.1 and 3.2) in the sliding regime.

The effectiveness of the proposed model is also demonstrated for a non-periodic input motion (a combination of the two signals: amplitude 0.5 rad and frequency of 0.2 Hz in and amplitude of 0.6 rad and frequency of $0.25\sqrt{3}$ Hz). Fig. 7(a) shows the time history of the input displacement signal. The ability of the proposed model to “capture” the characteristics of the nonlinear phenomena of the TSM is confirmed by a good agreement between the measured data and the model prediction. The comparison is illustrated in Fig. 7(b) and 7(c). The former figure presents the time history for the estimated friction values and experimental result while the latter introduces the error between the two set of values. For better comparison and observation, the mean square error, i.e. $MSE=0.0419$, is also used. Fig. 7(d) and 7(e) show the results for the relationship between friction with velocity and position. From these two figures, it has been verified that the proposed model can track quite well the measured friction force in the experiment, especially in the sliding regime where the hysteresis curves are separate and asymmetric. Finally, it has also been demonstrated that the estimated output tension T_{out} given in Fig. 7(f) shows a good agreement with the experimental data when the input tension T_{in} is available for measurement. The friction model is accurately estimated. From these results, it can be seen that the proposed model approach is not only efficient for periodic motion but also well suited for non-periodic motions.

6. Discussion

In this paper, we present the results of an investigation of a new dynamic friction model for tendon sheath actuated surgical system under arbitrary configurations of the sheath. Current model approaches in the literature utilize the Coulomb model, which has a discontinuity at small displacement that is not an accurate characterisation of the friction force in a TSM. The proposed model in this paper is able to represent the nonlinear friction for small displacements using a smooth function. In addition, at large displacements, it is able to predict accurately the asymmetric hysteresis force at the end effector of the system. This is due the fact that the proposed model uses velocity and acceleration dependent functions to represent the friction behaviour at various phases. Hence, the proposed model is able to provide continuous information of the tension at the distal end. However, this model is designed under several conditions such as the requirement of an initial pretension in order to avoid the tendon slack and no change of the accumulated curve angles during the operation.

With NOTES system like the MASTER robot [46], the tendon-sheath system is fixed in front of the surgical sites before surgical tasks are performed. Hence, there is a little change or no change of the sheath configuration in a real endoscopic system. To demonstrate that the proposed model is robust against configuration changes, although subject to the requirement that the total angle is maintained, experiments were conducted. Two configurations, shown in Fig 8(c) and 8(d) were considered. They have the same accumulated curve angles of 540° . Fig. 8(a) and 8(b) show the experimental results for the friction force as a function of velocity and position, respectively. It can be observed that there is no change or little change in the estimated friction force when the accumulated curve angles are maintained – note: this observation is confirmed by many experiments, but for illustrative purpose, only two of results are depicted only. Therefore, it can be concluded that the proposed model given by Eq. (5) to Eq. (13) can track well the friction force in the flexible TSM if the accumulated curve angles are constant.

From the above results, it can be asserted that the proposed model gives a better estimation of the friction force than that available in the current literature. In addition, the new model can adapt to any configuration and capture well both periodic and non-periodic motion of input signals.

7. Conclusion

Nonlinear friction force causes loss in the tension in the tendon-sheath system and it is hard to model. A commonly used model is the LuGre model, but it is not adept at predicting the force at small displacement where it changes rapidly. In this paper, we report on the investigation of a new dynamic friction model based on the modification of the LuGre model for the tendon-sheath mechanism where arbitrary configuration of the sheath and different motions are considered. Unlike the current approaches in the tendon-sheath model, the proposed model does not use the sheath curvatures, which introduces more difficulties in complex routes and measurement of curve configuration. Instead of using lumped mass model parameters, the model considers the whole tendon sheath as an element and uses the solution of a unique differential equation to capture the nonlinear hysteresis for both small and large displacements. By integrating the velocity and acceleration information in the sliding regime, the asymmetric loops and separate hysteresis curves are well captured. In comparison with current approached in the literature, the proposed model has demonstrated that the tension at the distal end of the tendon-sheath system can be predicted quite well at areas near zero velocity where the system is stationary or at small displacement. In addition, the proposed model is also able to predict accurately the friction force when the system is in the sliding regime (large displacement). An efficient identification process has been used to derive the model parameters. The new model is subsequently verified using comparisons between experimental data and the estimated values. It has been shown that the proposed structure is not only able to adapt to periodic motion but also to non-periodic motion.

Future activities will focus on the design of nonlinear control schemes for the proposed model when the system is subjected to tremor and online change of accumulated curve angles during the operation. In addition, a haptic device, using the estimated friction force, will be utilized during in-vivo experiment to provide accurate force information to the surgeon.

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Figure(s)

Figure 1: Tendon-sheath mechanism and its friction force characteristics.

Figure 2: Single bristle represents the average deflection in LuGre model [29]

Figure 3: Results for the LuGre model: (left) Friction vs. Velocity; (right) Friction vs. Position

Figure 4: Simulation result for the sliding functions S_{+v1} and S_{+v2} versus relative velocity ($\dot{x} = 18.75 \cos(3.75t - 1.56)$) with parameters $\rho_1 = 8.855$, $\mu_1 = -6.533$, $\kappa_1 = -0.341$, $\kappa_2 = 0.078$, $\kappa_3 = 0.0063$, $\mu_2 = 14.6$.

Figure 5: The experiment setup

Figure 6: Comparison results between measured data from experiment and the proposed model for periodic motion of signal with frequency of 0.2 Hz in and amplitude of 1 rad.

Figure 7: Comparison results between measured data from experiment and the proposed model for non-periodic motion of input excitation (a combination of the two signals: amplitude of 0.5 rad and frequency of 0.2 Hz and amplitude of 0.6 rad and frequency of $0.25\sqrt{3}$ Hz)

Figure 8: Experimental results for different curve shape of the TSM: (a) Friction vs. Velocity; (b) Friction vs. Position; (c) Configuration-Shape 01; (d) Configuration-Shape 02.

(a) Tendon-sheath mechanism

(b) Relation between friction force and motions: (Left) friction vs. velocity; (Right) friction vs. position.

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(a) Photograph of experimental rig

(b) Schematic of experimental setup

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