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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 behavior 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.

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.

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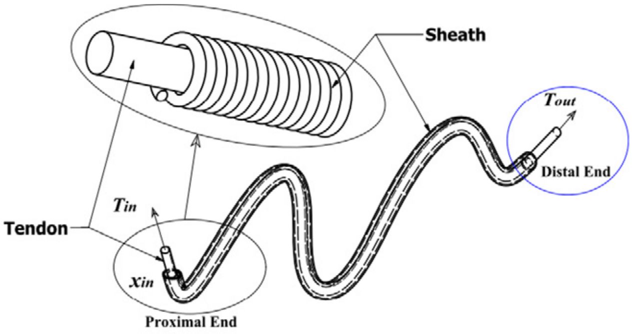
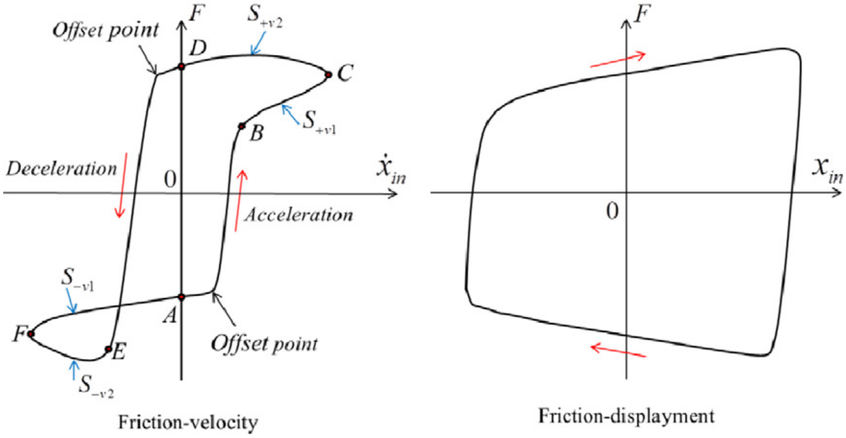
Various analytical model parameters of friction and transmission for the TSM using lumped mass model combined with Coulomb friction model are available in literatures. Kaneko et al. [9–11] provided a discrete lumped mass model using Coulomb friction model. Palli et al. [12,13], Sun et al. [14], and Low et.al [15] modeled 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 modeled 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] modeled 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 demonstrate asymmetric hysteresis profile in the acceleration and deceleration directions, there is a significant 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 and the behaviors in both directions are completely different. In positive velocity, the tendon-sheath friction force increases in 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



(a) Tendon-sheath mechanism



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

Fig. 1. Tendon-sheath mechanism and its friction force characteristics.