Force Propagation Models in Laparoscopic Tools and Trainers

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Abstract

Most of the tools that are used in performing manipulation tasks in laparoscopic surgery are graspers and needle drivers. Although the operation of such basic tools are rather simple, but in combination with remote access to the surgical site and in-direct field of view makes the usage of such mechanisms challenging. This makes the surgeons undergo a series of training for gaining proper hand/eye coordination. In addition, due to the structure of these mechanisms, the sense of touch has been reduced to minimum. One challenge of research and development has been to design a force reflective graspers that can reflect the sense of touch back into the handle. In addition, considerable effort are being focused on developing a virtual laparoscopic trainers where the sense of touch in manipulating the virtual tissues and organs can be reflected to the hand of the surgeon through proper design of haptic interfaces. This paper presents force propagation models which can be used in modelling, design and interpretation of the force sensing system and reflecting devices. The proposed models agree with the experimental observation previously published in the literature for describing the relationships between the magnitude of grasping force and the applied force at the handle.

1. Introduction

The modern era of laparoscopic surgery began when a miniature video camera was attached to the eyepiece of the laparoscope allowing several people to view the operation on the television monitor. There are many advantages associated with *minimally invasive surgery(MIS)* such as laparoscopic surgery. These mostly benefit the patients and the health service organization. However there exist some limitations associated with the current practise in the area of instruments and system designs[1][2][3].

One of these limitations is the lack of haptic sensation. An experimental studies by [4][5] have characterize the relationships between the forces at the handle of the laparoscopic tools and at the tip of the graspers. The experimental results have pointed-out to the nonlinear relationships between the input/output forces and hence the lost of direct sensation of the magnitudes of forces in manipulating various tissues and organs. To overcome these limitation, design concepts are being proposed for increasing the sense of grasping forces at the handle as a function of the tip forces (haptic interfaces), e.g. [6][7][8]. These designs can also be used by the surgeons in gaining hand/eye coordinations in performing such operations in a simulated environment. This simulator will allow the surgeons to interact with graphical simulation of virtual laparoscopic environment through a computer interface mechanism. This mechanism in addition to moving a virtual graspers or needle drivers, it can also create a sense of compliant feedback at the hand of the surgeon as a function of pushing, holding or squeezing a virtual tissue or organs. Some of the steps in designing such systems are: a) determination of relationships between the magnitude of the sensed of force at the hand of the surgeon and the tip grasping force; b) design of such surgeon interface mechanism; c) a measure for calculating the desired tip grasping force as a function of the location of the virtual graspers in relation to the virtual organ and tissue.

This paper presents models and relationships which

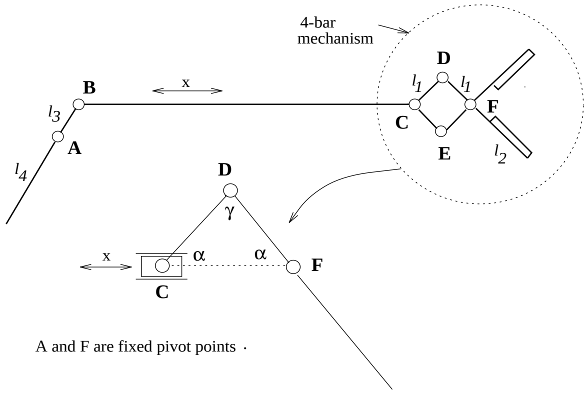

Figure 1: Kinematic parameters of a simple grasper/needle-driver

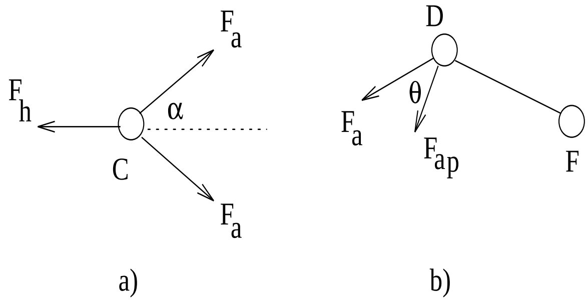

Figure 2: Force propagation models at the four-bar mechanisms configuration

can be used to understand the force propagation in designing advanced graspers/needle drivers and force-reflecting systems.

2. Basic Relations

This section develops some basic relationships which can be used to study interconnections between the kinematic parameters of the laparoscopic tools and the force propagation in such mechanisms.

Figure (1) shows a basic schematic representing a generic grasper/needle driver mechanism which is used in laparoscopic surgery. In general, most designs involve a handle mechanism, the transmission link and the grasper four-bar mechanism. Referring to Figure (1), and Figure (2a) we can write the following relationship between the linear displacement x and angle α:

$$cos(\alpha) = \frac{2l_1 - x}{2l_1} \tag{1}$$

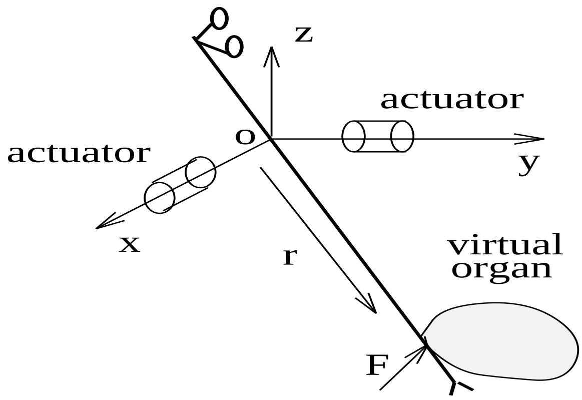

Figure 3: A schematic example of a laparoscopic trainer

from the Figures the angle beteen the two links CD and DF namely γ ,can be obtained to be:

$$\gamma = \pi - 2\alpha \tag{2}$$

The other kinematic parameters which defines the angle between the perpendicular to the link DF, and the link CD can be calculated to be: (Figure 2b)

$$\theta = (\gamma - \frac{\pi}{2}) \tag{3}$$

Using the above kinematic parameters, we can now define the force propagation models through-out the mechanism. Referring to Figure (2b), we have:

$$F_{ap} = F_a cos(\theta) \tag{4}$$

F_{ap} is the effective force which can cause a net moment about the fixed pivot point F.

Let F_h is the net force being transmitted from the handle mechanism. In equation (4), the force F_a can be obtained as a function of force F_h and α as:

$$F_a = \frac{F_h}{2cos(\alpha)} \tag{5}$$

In the above and from the Figure (1), the input force from the hand of the surgeon F_p and the force transmitted to the rod of the grasper F_h is related through the following relationships:

$$F_h = \frac{F_p l_4}{l_3} \tag{6}$$

The above relationships were concern with the internal force propagation models through the laparoscopic tools. Figure (3) shows a schematic example of a virtual laparoscopic trainer. Here, the force propagation model is the relationship between the applied torque at the active joints of the trainer as a function of the calculated force $\vec{F}$ generated through graphical simulation. This relationship can in general be written as:

$$\vec{M} = \vec{r} \times \vec{F} \tag{7}$$

where $\vec{r}$ is the position vector representing the location of the net calculated force $\vec{F}$, i.e $\vec{r} = r_x i + r_y j + r_z k$ and $\vec{F} = F_x i + F_y j + F_z k$. The force vector $\vec{F}$ is the force generated by for example pushing a virtual organ. This force vector can be evaluated through following relationship:

$$\vec{F} = K\vec{\Delta r} + C\dot{\vec{\Delta r}} \tag{8}$$

where K and C are the estimated or planned stiffness and damping matrix parameters of the tissue/organ or the impedance parameters of the executed tasks such as suturing/knotting/cutting[9]. $\vec{\Delta r}$ is the position vector difference.

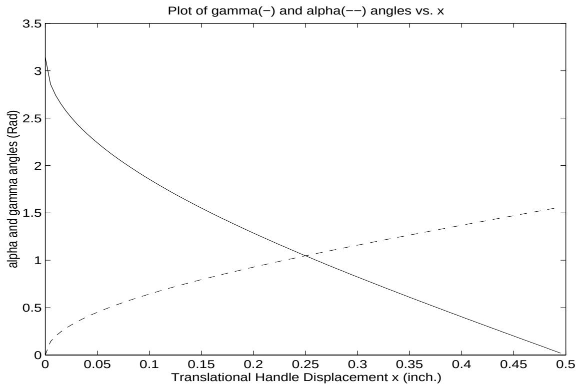

Figure 4: Variation of kinematic parameters γ and α as a function of the displacement x of the connecting rod

3. Results and Discussions

Previous section presented some relationship between the kinematic parameters and the propagation forces in a typical tool. In this section, we will study how these parameters vary as a function of input parameters from the handle of graspers.

Figure (4) shows the variations of the angles γ and α as a function of linear translation of the grasper handle rod x. It can be seen that there is a non-linear relationships between the linear and angular kinematic parameters.

Figure (5) shows variation of the force propagation components F_{ap} and F_g as a function of the displacement x. These results are obtained by setting the magnitude of input force from the handle F_p equal to $1lbf$ during the entire range of travel of x. As it can be seen from the Figure, there is a non-linear relationship between these force propagation models for a given F_p. Especially the tip grasping force F_g, for a given $F_p = 1lbf$, reaches its maximum during the interval of motion x when the grasper is wide open and drops to low magnitude as a function of closing angle of the jaws. These relationships remains the same when the magnitude of F_p is varied within the practical regions.

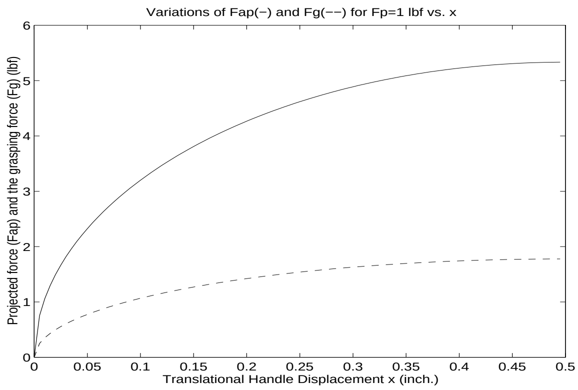

Figure 5: Variations of force propagations F_{ap} and F_g as a function of kinematic parameters

Figure (6) shows variations of the tip grasping force F_g as a function of the handle force F_p exerted by the

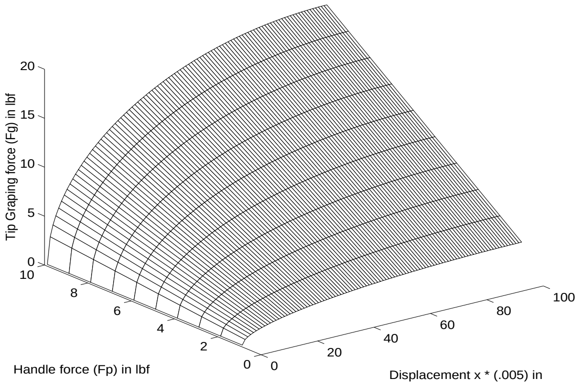

Figure 6: Relationship between the tip grasping force F_g as a function of the input force F_p and the linear displacement x of the connecting rod.

user and the linear displacement x of the connecting mechanism. These results also agree with the experimental observation of [4][5] where they observe a nonlinear relationship between the input force F_p at the handle of laparosopic tools and the the grasping force F_g exerted on the tissues and organs.

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