Evaluation of Compliant Handle for Endosurgical Grasper using Pseudo-Rigid-Body Method

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ABSTRACT

The endosurgical grasper is a tool used for tissue manipulation in an endoscopic surgery. By adding a controller into the device, a surgeon can control both the grasping and the input forces. However, it will increase the number of components in the device. This objective of this design is to use the virtue of a compliant material to minimise the number of device components and at the same time keeping the output performance as same as the datum. The mechanism design is analysed using pseudo-rigid-body method. The results have shown that, by decreasing the length of the spring to at least 78% will save about 86.6% of its maximum size. Therefore, the surgeons will feel more comfortable when handling the device as a few of its components, size and weights have been reduced.

Keywords: *Endosurgical Grasper; Compliant Mechanism; Pseudo-Rigid-Body Method*

Nomenclature:

r'	Transmission ratio or mechanical advantage
F_{in}	Handle force, (N)
F_s	Spring force, (N)
F_{out}	Output force at the tip of the grasper, (N)
X_{in}	Input displacement, (mm)
X_s	Spring deflection, (mm)
X_{out}	Tip displacement, (mm)
g	Characteristic radius, (mm)
K_q	Stiffness constants, (N/mm)

Introduction

Minimally Invasive Surgery (MIS)

Minimally Invasive Surgery (MIS) is a new kind of surgery, which becoming more popular nowadays. Other well-known expressions are 'Endoscopic Surgery' [1], 'Laparoscopic Surgery (LS)' or 'Minimal Access Surgery (MAS)' [2]. The operation is different from Open Surgery (OS) in many aspects such as from surgical instruments that are going to be used, recovery time, types of problems faced, until cost of operation and equipments. Moreover, patient obtains various advantages from this method of operation [2], [3]. However, it is a difficult process to doctors. The problems like restricted vision, difficulty in handling of the instruments, a very restricted mobility, difficult hand-eye coordination and no tactile perception are some important disadvantages for them [3], [4].

MIS begins with three to five small incisions through which surgeon inserts narrow, tube-like devices called trocars. Through these trocars, the surgeon inserts a laparoscope and other instruments such as graspers, needle-drivers and scissors. While watching a 3-D video monitor, the surgeon manipulates the surgical instruments to perform the same operations as would take place during a traditional open surgery. But sometimes, because of poor force-deflection property of the endosurgical grasper, i.e. it does not reflect the grasping force of the hand of the surgeon and there exists the possibility of damaging delicate tissues [5].

The primary cause to the above problem is due to many components in the device which causes some of energy lost due to friction. By reducing the number of components can keep this problem lower. Another factor that contribute to the problem is due to the application of closed loop system, which can control the output force and limit the input force [4], [5], [6]. Payandeh in his paper [5] had introduced haptic feedback based on the notion of the tunable spring. The transmitted force, F_{out} at the grasper is found to be proportional to input force, F_{in} based on a determined transmission ratio, r'. However, this will cause adding the number of components, weight and size.

The purpose of this study is to analyze the suitability of a compliant material in reducing the number of components, weight and size. The potential parts that are capable to be made compliance are handle and spring components. By making datum's capability as design constraints, the analysis is carried out by changing those specifications such as the size and the type of material that will be used. The iterations will be done until difference between the compliant design and the datum performances become smaller.

Compliant Mechanisms

Compliant mechanism performs by gaining at least some of their mobility from the deflection of flexible members rather than from movable joints only. By now, there are many examples of compliant mechanisms that have already been designed to do such a specific work and their performances are better than previous rigid body mechanism [7]. For the same design, the number of components in compliant mechanism is lesser than rigid body mechanism. Some can be reduced to one or two components only and is produced through process of injection molding, rapid prototyping, or other manufacturing processes.

The component reduction from the use of compliant mechanism, without reducing datum performance, gives advantages to doctors and patient. A device becomes more compact, easy to handle and use and more importantly is reducing fatigue to doctor's hand as its weight has been decreased.

However the greatest challenges in compliant mechanisms are analyzing and designing them. Much of the current compliant mechanism design is performed without the aid of a formal synthesis method and based on designer's intuition and experience [5]. Several trial and error iterations using finite element models are often required to obtain the desired mechanism performance.

Since the existing methods for designing rigid-link mechanisms do not account for material deformation, therefore, they are inadequate for the design of compliant mechanism, which permit large deformation within the members [5]. The two approaches known in the literature for the systematic syntheses of compliant mechanisms are the kinematics based approach [8] and the structural optimization–based approach [9], [10], [11], [12]. Methodology for designing compliant handle will be discussed in Section 2.

The paper has five main sections; Section 1 is the introduction, Section 2 discusses the approach used, Section 3 shows the analysis of compliant mechanism, Section 4 discusses the results obtained, including the performance of compliant mechanism, comparison to the conventional design and materials considerations and Section 5 presents the conclusions.

Design Approach

As a design uses the material that is flexible, the Hooke's law cannot be used to find design properties when designing rigid body mechanism. The design analysis will become more difficult, but it can be made easy by altering the structure to be compliant using pseudo rigid body method.

The pseudo-rigid-body method is used to simplify the design and the analysis of compliant handle. It combines between rigid-body mechanism theory and compliant mechanism theory. By using this method, the analysis is performed by modeling the compliant members as cantilever beams. From the beam model, an equivalent rigid member and torsional spring model is developed to approximate the deflections [7]. This method begins with a known rigid-link mechanism, and an iterative process generates an appropriate compliant mechanism design.

The objective is using compliant material to minimize the number of device components without decreasing datum performances. The analysis is repeated by using the updated values until the objective and constraints are satisfied.

We shall first analyze the mechanism by generating all the mathematical equations necessary and then, the results obtained will be compared to the previous design and discussed. On the whole, design approach that will be carried out is as being shown in Figure 1.

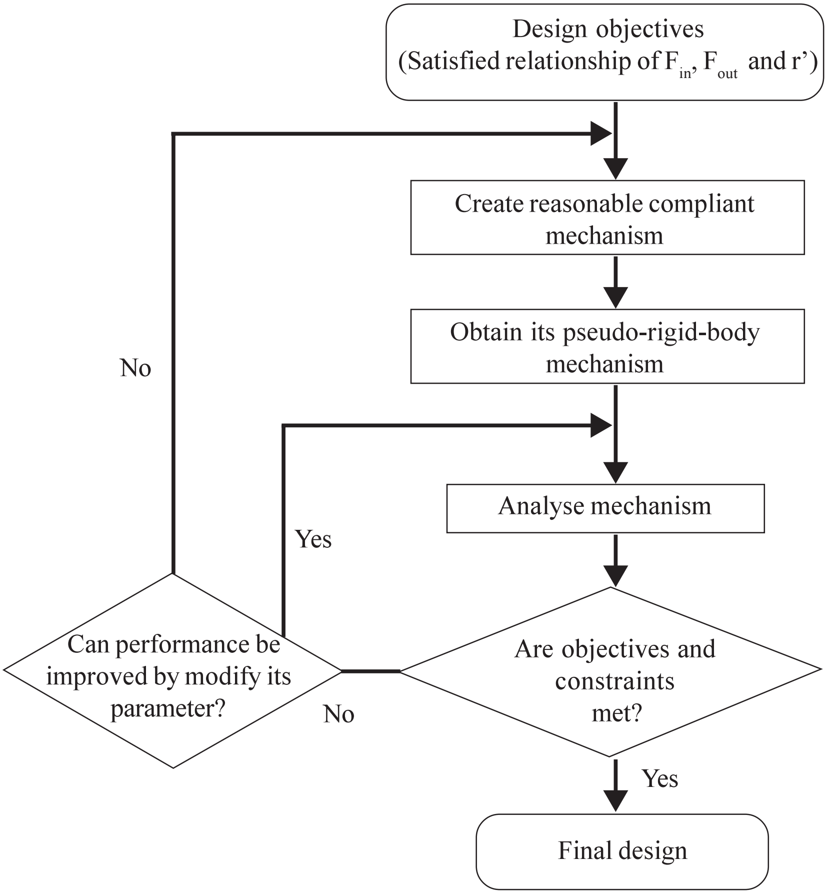
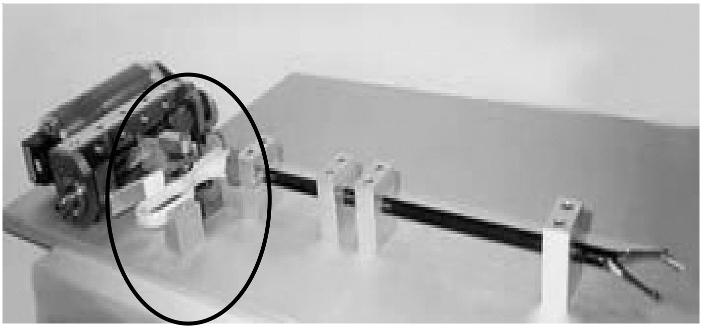


Figure 1: Design Flowchart for Compliant Handle for Endosurgical Grasper

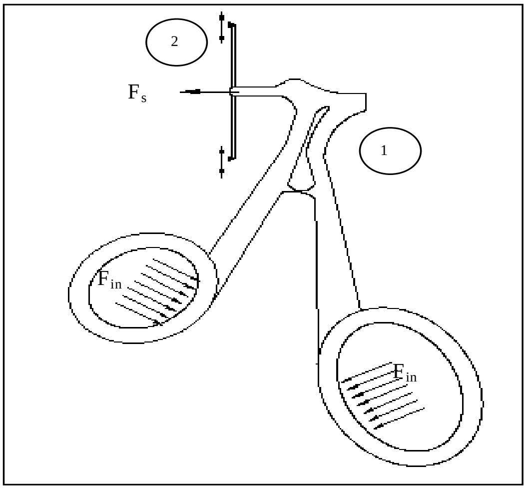
Analysis of Mechanism

Mechanism Description

Figure 2 (a) shows a design concept for a grasper, which limits the amount of force that gets transmitted from handle of the grasper to its tip. The design allows the surgeon to tune the magnitude of force transmission based on his/her gripping force capabilities. The design is based on the notion of the tunable spring and direct sensation of the gripping forces. Figure 2 (b), shows a proposed design of a compliant handle for endosurgical grasper with forces acting on it.



(a)



(b)

Figure 2: (a) Datum Design (Circled), and (b) Design of a Compliant Handle

The design of a compliant handle is analysed in two parts:

1. A handle mechanism
2. A tuneable spring, which its length can be controlled.

The input force, F_{in} that is applied by surgeon to the compliant handle will generate a reaction force, F_s, acting in the middle of the spring. The assistance of the controlling mechanism controls spring's length, depending on the required output force, F_{out} for the different manipulated tissue.

The challenges come when to find the optimum size of the tuneable spring that can deflect without reaching its yield point and at the same time keeping the required performances approximately as the datum.

Pseudo-rigid-body Analysis: Handle Mechanism

The analysis starts by finding spring force, F_s that resulted from applied input force, by using the concept of virtual work. Only half handle is analysed due to symmetry in its geometry.

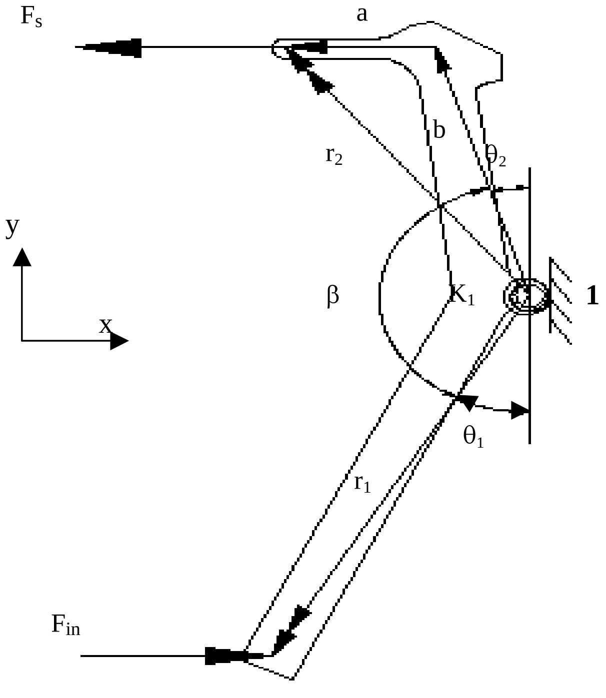


Figure 3: Pseudo-rigid-body Model for Handle Mechanism

Relationship of spring force, F_s to angular displacement, θ_1

Step 1: θ_1 is chosen as a generalized coordinate.

Step 2: Express applied and reaction forces in vector form. (Assuming that both forces are moving in horizontal direction)

$$\overline{F}_1 = F_{in}\ \overline{i}$$

and,

$$\overline{F}_2 = -F_s\ \overline{i}$$

Step 3: Determine a position vector for each force in step 2.

$$\overline{r}_1 = -(r_1 \sin\theta_1\ i + r_1 \overline{\cos}\ \theta_1\ j)$$

and,

$$\overline{r}_2 = -(a + b\sin(\theta_1 + \beta))\ \overline{i} - (b\cos(\theta_1 + \beta))\ \overline{j}$$

Step 4: The virtual displacement is found by differentiating the positions vector with respect to the generalized coordinate, θ_1.

$$\delta\overline{r}_1 = -r_1 \cos\theta_1\ \delta\theta_1\ \ \overline{i} + r_1 \sin\theta_1\ \delta\theta_1\ \overline{j}$$

and,

$$\delta\overline{r}_2 = -b\cos(\theta_1 + \beta)\ \delta\theta_1\ \overline{i} + b\sin(\theta_1 + \beta)\ \delta\theta_1\ \overline{j}$$

Step 5: The virtual work due to the forces and the virtual displacement.

$$\delta W_1 = \overline{F}_1 .\ \delta\ \overline{r}_1 = -F_{in}\ r_1 \cos\theta_1\ \delta\theta_1$$

and,

$$\delta W_2 = \overline{F}_2 .\ \delta\ \overline{r}_2 = F_s\ b\cos(\theta_1 + \beta)\ \delta\theta_1$$

Step 6: The potential energy for the spring at point 1.

$$V = K_1/2\ (\theta_1 - \theta_0)^2$$

Step 7: The virtual work from potential energy.

$$\delta W_2 = -(dV/d\theta_1).\ \delta\theta_1 = -K_1\ (\theta_1 - \theta_0)\ \delta\theta_1$$

Step 8: Total virtual work.

$$\begin{aligned}\delta W_T &= \delta W_1 + \delta W_2 + \delta W_3 \\ &= - F_{in} r_1 \cos\theta_1\, \delta\theta_1 + F_s\, b \cos(\theta_1 + \beta)\, \delta\theta_1 - K_1(\theta_1 - \theta_0)\, \delta\theta_1\end{aligned}$$

Step 9: Applying the principle of virtual work: If in equilibrium, the virtual work is equal to zero ($\delta W_T = 0$).

$$-F_{in} r_1 \cos\theta_1\, \delta\theta_1 + F_s\, b \cos(\theta_1 + \beta)\, \delta\theta_1 - K_1 (\theta_1 - \theta_0)\, \delta\theta_1 = 0$$

$$F_s = \frac{K_1 (\theta_1 - \theta_0) + F_{in} r_1 \cos\theta_1}{b \cos(\theta_1 + \beta)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Relationship of spring force, F_s to input displacement, X_{in}

From $s = \Delta D\theta$, then,
Input displacement, $X_{in} = r_1\, \Delta\theta_1$
And,

$$F_s = \frac{K_1 (X_{in}/r_1) + F_{in} r_1 \cos(X_{in}/r_1)}{b \cos((X_{in}/r_1) + \beta)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Finding spring deflection, X_s

Spring deflection, X_s is calculated using pseudo-rigid-body method.

Iterative solution:

Step 1:

$$F_s\, \eta\gamma\, l \sin(\pi/2 - \Theta) - K_2\, \Theta = 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

where $K_2 = \dfrac{K_\Theta\, g\, E\, I}{l}$

Since only vertical force acting at the middle point of the spring, F_s, so from Table 5.1 in reference [5]:

$\eta = 1$
$\gamma = 0.8517$
$K_\Theta = 2.67617$

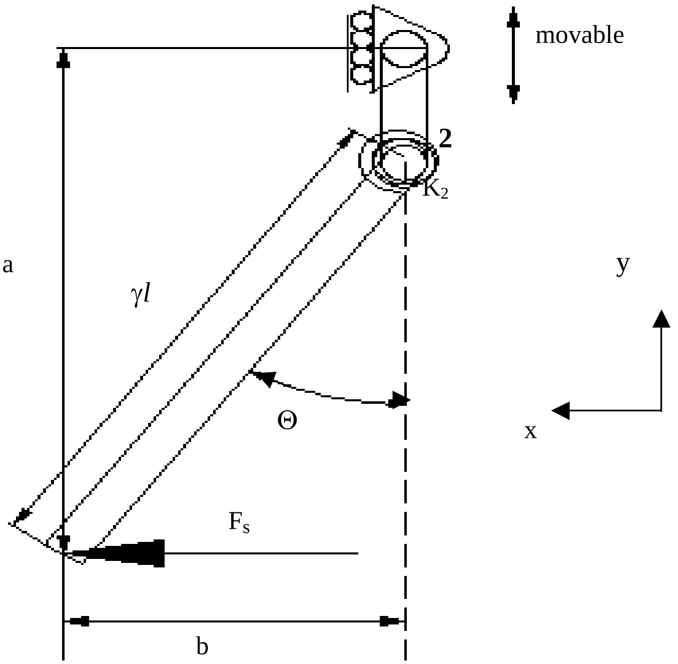


Figure 4: Pseudo-rigid-body Model for Spring Mechanism

The pseudo-rigid-body angle, Θ must be calculated iteratively before the horizontal and vertical deflections can be determined.

Step 2:

Vertical deflection,

$$a = l\,[1-\gamma(1-\cos\Theta)] \qquad \text{……………………(4)}$$

Spring or horizontal deflection,

$$b = X_s = \gamma l \sin\Theta \qquad \text{……………………(5)}$$

Output force, F_{out} calculation

F_{out} can be calculated by using this equation: -

$$F_{in} = r_s F_s + r\ F_{out} = (X_s / X_{in})\, F_s + (X_{in} / X_{out}) F_{out}$$

$$F_{out} = \frac{F_{in} - (X_s / X_{in})\, F_s}{(X_{in} / X_{out})} \qquad \text{……………………(6)}$$

Mechanical advantage or transmission ratio, r' calculation

The values of F_{out} from (6), are then divided to F_{in} to get r'.

Mechanical advantage, $r' = F_{out} / F_{in}$ ……………………(7)

Maximum stress calculation

(a) For tuneable spring,

$$\text{Stress} = \frac{6 F_s l}{w t^2} \qquad \text{……………………(8)}$$

(For tensile, σ_t and compressive stresses, σ_b)

(b) For small length flexural pivot which is located at the handle,

For compressive stress

$$= \frac{3 F_{in}}{4 w t}\left(\frac{6 b}{t} + 1\right) \qquad \text{……………………(9)}$$

For tensile stress

$$= \frac{3 F_{in}}{4 w t}\left(\frac{6 b}{t} - 1\right) \qquad \text{……………………(10)}$$

Mechanical advantage, r'

A compliant mechanism should be flexible so that it can easily deform, but it should also be stiff enough to provide an adequate mechanical advantage [5]. The mechanical advantage of a compliant mechanism may vary as a function of the energy stored in the flexural pivots, the initial and final orientations, the method of loading, and the flexible and rigid segment dimensions [5]. It is actually equal to F_{out}/F_{in}. It is important in order to get the accurate output force when we apply input force at a different setting of transmission ratio. To achieve this goal, we have to do the calculation as stated in 3.2 iteratively. The results shown in Figure 5(a) – 5(k) are obtained after all constraints are considered.

Results and Discussion

Analysis of Result

The analysis of results demonstrate the potential of a compliant handle to meet the present goals and requirements. The ability is verified by graphs shown in Figure 5(a) – 5(k). The maximum stresses caused by externally applied forces in those mechanisms are stated in 4.1.2. Furthermore, both designs are compared through their design performances and abilities at different setting of transmission ratio in section 4.2.

The relationship of F_{in} for both datum and compliant handle design to mechanical advantage, r'

The purpose of this design is to develop such mechanism that is able to transmit the input force at the handle to the output force at the end tip of the grasper at every transmission ratios determined by the surgeon. These ratios are varying from 0.1 to 1.1. In this paper, these ratios are also called mechanical advantage, r' which is the ratio between the output and input forces.

The relationships of F_{in} for both datum and compliant handle design to mechanical advantage, r' at every determined transmission ratio are shown in Figure 5 (a) – (k). From that figures, we can see that all lines represent compliant mechanism are fluctuating around its datum line. The differences can be clearly seen when r'= 0.7 and above. However, the variation is still too small, which is just around ± 0.00025 of the datum.

Maximum stress in mechanisms

(a) For tuneable spring.

Table 1: Maximum Stresses in Spring at Different Setting of Mechanical Advantage, r'.

r'	Max. F_s (N)	Length, l (mm)	σ_t and σ_b (MPa)
0.1	17.685	4.5	33.16
0.2	17.531	5.5	40.18
0.3	17.422	6.0	43.56
0.4	17.316	6.5	46.90
0.5	17.239	7.0	50.28
0.6	17.075	7.5	53.36
0.7	16.910	8.0	56.37
0.8	16.724	8.5	59.23
0.9	16.628	9.0	62.36
1.0	16.458	9.5	65.15
1.1	16.341	10.0	68.09

Table 1 shows that increase in length will affect much in the spring stress. This satisfies conventional beam theory. However it seems contradictory with respect to relationship of the maximum force and stress, where the stress increases as force is decreased. Though, the maximum stress is below than 70 MPa and it occurs at the end of spring constraint

(b) For a small length flexural pivot

Since the pivot is located between the handles, the stress concentration is higher at this point. Therefore, the maximum stress is limited to 150 MPa. The reason for this is that the combine effect of force times length i.e. bending moment, generates the stress.

The Comparison between Conventional Design and Compliant Handle

We perform a comparison at spring specification, its output performance in both design and material selection.

Spring Specification

Table 2: The Comparison between Datum and Compliant Design Specifications

	Spring thickness, t (mm)	Spring width, w (mm)
Datum	1.6	12.5
Compliant	1.2	10.0

From Table 2, we know that by using a compliant spring, reduce spring thickness can be reducing until 25% from its conventional design while 20% for its width. Meaning, for the same length, we can decrease about 40% from its previous size and 90% in weight.

Table 3 shows that in order to gain mechanical advantage increment of 0.1 the datum needs incremental length of 4.0mm whereas compliant design needs only 0.5mm. Thus, for the same output performance, we can save at least 78.0% length of the spring and decrease about 86.6% of its maximum size.

Table 3: Comparison between datum and compliant design at different setting of mechanical advantage, r'

r'	Length of the spring, l(mm)	
	Datum	Compliant
0.1	4.0	4.5
0.2	8.0	5.5
0.3	12.0	6.0
0.4	16.0	6.5
0.5	20.0	7.0
0.6	24.0	7.5
0.7	28.0	8.0
0.8	32.0	8.5
0.9	36.0	9.0
1.0	40.0	9.5
1.1	45.0	10.0

Although the value of r' for both designs (compliant and conventional) are nearly same, however, this does not occur in output displacement, as shown in Figure 6. The output displacement, X_{out} measures the size of tissue that grasper can grasp. Increasing in X_{out} means the grasper can grasp larger tissue. As in datum, X_{out} is proportional to F_{out}. A larger tissue needs more force to grasp. But as we can see in Figure 6, this is not valid in compliant design especially when r' is equals to 0.5 and 0.8. As the result, we can see that, the line is fluctuating compared to conventional design. It shows much of difference at the beginning, but seems to be same at the end value of r'. Besides, for same output force, the range of its maximum output displacement has been reduced to approximately 88% from previous design.

Material Considerations

Basically, the best material choice for compliant mechanism is a polymer. It is due to its low manufacturing cost in high volume, high ratio of strength Young's modulus and machinability. The material with the highest strength-to-modulus ratio, s_y / E is much better, where mechanism can go for larger deflection before failure. This ratio is one of the most important parameters available in compliant mechanism applications. Table 4 shows several materials that can be best fitted for these compliant spring and handle. Those materials are found from http://www.matweb.com/ based on iteratively calculation done in section 3.2.3 and 3.2.6.

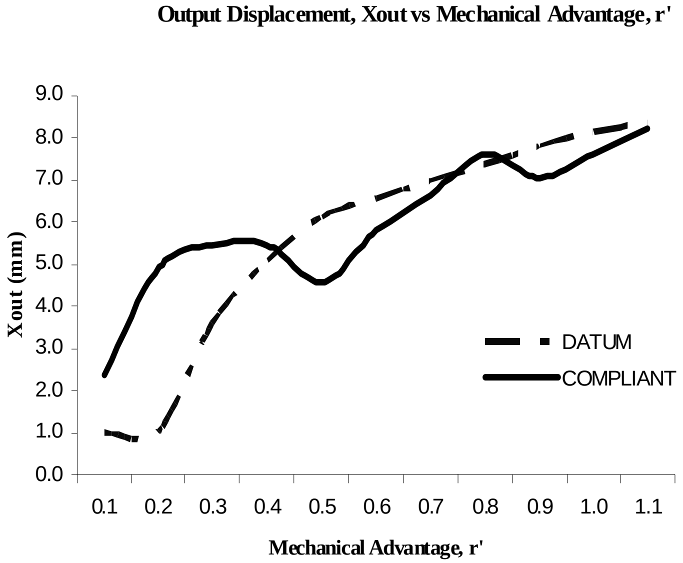


Figure 6: Output Displacement X_{out} versus Mechanical Advantage, r'

Table 4: Ratio of Yield Strength to Young's modulus for Several Materials

Material	E (GPa)	σ_y (MPa)	(σ_y/E) x 1000
Nylon, Barrier Film Copolymer	0.37	100	270.27
Nylon 6, Unreinforced	0.37	100	270.27
Nylon 6, 40% Glass Fibre Filled	13.0	200.0	15.38
Nylon 610, Glass Reinforced	13.0	193.0	14.85

Discussion

The purpose of designing and analysing these compliant spring and handle are to reduce some components in the controllable endosurgical grasper. From this study, the design tries to reduce five components to only two. Thus, minimize the opportunity of the input force lost as a frictional energy. From manufacturing point of view, the reduction in part count will make assembly become much easier and reduce the production cost especially when produced in high volume.

From the graphs shown in Figure 5(a) – 5(k) and Figure 6, we see that, the relationship between F_{in} and F_{out} to mechanical advantage, r' for compliant handle is nearly satisfying datum performance. The values vary only ± 0.00025 from its datum. Moreover, the size of spring used is also reduced as shown in Table 2 and 3. This make the device become more compact and easy to handle as some of its weight has been reduced. For the same output performance, we can save at least 78.0% in length of the spring and decrease about 86.6% of its maximum size. Besides that, the motor power that is used in the control mechanism can also be lowed as the decreasing of length, *l*.

As shown from Table 4, Young's modulus for spring should be smaller compared to handle. Therefore it can deflect more. The maximum stress calculated for the spring occurred at both of its ends, while for the handle, the maximum stress is predicted to occur at a small length flexural pivot, which is located between the handles, and it is limited to 150 MPa.

Conclusion

This paper presented a design and analysis of a compliant handle in endosurgical grasper using pseudo-rigid-body method. From the above study, we see that, the compliant handle has a potential to replace a conventional handle due to reduction in its size and weight. These advantages will bring less fatigue to surgeon's hand and at the same time increase force-deflection property of the endosurgical grasper. However, there is still lot of works to be done such as experimentally analysis where the proposed design of compliant handle is made and its performance is tested.

Acknowledgements

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