Effects of Geared Motor Characteristics on Tactile Perception of Tissue Stiffness

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Abstract

Endoscopic haptic surgical devices have shown promise in addressing the loss of tactile sensation associated with minimally invasive surgery. However, these devices must be capable of generating forces and torques similar to those applied on the tissue with a standard endoscopic tool. Geared motors are a possible solution for actuation; however; they possess mechanical characteristics that could potentially interfere with tactile perception of tissue qualities. The aim of the current research was to determine how the characteristics of a geared motor suitable for a haptic surgical device affect a user's perception of stiffness. The experiment involved six blindfolded subjects who were asked to discriminate the stiffness of six distinct silicone rubber samples whose mechanical properties are similar to those of soft tissue. Using a novel testing device whose dimensions approximated those of an endoscopic grasper, each subject palpated 30 permutations of sample pairs for each of three types of mechanical loads; the motor (friction and inertia), a flywheel (with the same inertia as motor), and a control (no significant mechanical interference). One factor ANOVA of the error scores and palpation time showed that no significant difference existed among error scores, but mean palpation time for the control was significantly less than for the other two methods. These results indicated that the mechanical characteristics of a geared motor chosen for application in a haptic surgical device did not interfere with the subjects' perception of the silicone samples' stiffness, but these characteristics may significantly affect the energy expenditure and time required for tissue palpation. Therefore, before geared motors can be considered for use in haptic surgical devices, consideration should be given to factors such as palpation speed and fatigue.

1. Introduction

Shorter hospital stays, decreased probability of infection, and minimal scarring are just a few of the many advantages associated with minimally invasive surgical techniques. Nevertheless, in exchange for these advantages, surgeons have typically been forced to use endoscopic surgical tools that convey only a fraction of the tactile information received with open surgical techniques [1,2]. Because tactile information regarding tissue properties, such as stiffness, is critical to the diagnosis of a full range of pathologies, a great deal of effort has been devoted to increasing tactile sensation [3]. Certainly, one of the more promising solutions to this problem, is the development of force-feedback endoscopic surgical devices. Previous research with a direct drive haptic surgical device has demonstrated the ability to relay tactile information between the grasping and handle ends of a teleoperated endoscopic grasper [4]. Nevertheless, in order to perform surgical tasks, these devices must be capable of producing forces and torques similar to those applied by surgeons using regular endoscopic instruments. One promising means of actuation is a geared motor, which offers a compact and efficient means of producing the necessary torque.

Although a high gear ratio ensures sufficient torque output from the motors, it also introduces undesirable effects such as friction forces, inertial effects, and gear cogging, which may limit a user's ability to perceive the characteristics of material being grasped by the device. These problems associated with a geared motor interference are not new, and efforts have been made to reduce these effects using control algorithms and force sensing. However these solution lead to added costs and challenging stability problems. Furthermore, the effects of the geared motor characteristics on perception of tissue properties are unknown, and this information is critical to determining the feasibility of using geared motors in haptic surgical devices.

The objective of this study was to test the effects of geared motor characteristics on perception of tissue stiffness and in particular to:

- Determine if a geared motor suitable for use in an endoscopic surgical tool produces motor characteristics that impair perception of stiffness.
- Examine how geared motor characteristics effect tissue palpation and perception of tissue stiffness.
- Begin exploring which characteristics are responsible for decreased perception.

2. Tools & Methods

2.1 Geared Motor Selection

A geared motor used in a hand-held haptic surgical device must be as physically small and lightweight as possible while still maintaining sufficient torque production capacity. Additionally, as friction force and inertia increase by the square of the motor's gear ratio it is important to minimize this value. Although, the motor selected for this experiment was only used as an open-circuited mechanical load, it was selected according to these design constraints. Based on kinematics analysis for a typical endoscopic grasper and measurements performed during minimally invasive surgery, a maximum continuous torque output of 1.5 Nm is required of the actuator. The maximum allowable motor weight was limited to 0.5 Kg. A number of geared motors were compared according to their total weight, maximum torque production, and gear ratio. The motor that most accurately satisfied the desired design constraints was a Maxon 70 Watt DC Motor with a 23:1 planetary gearhead (Fig 1, dark circle).

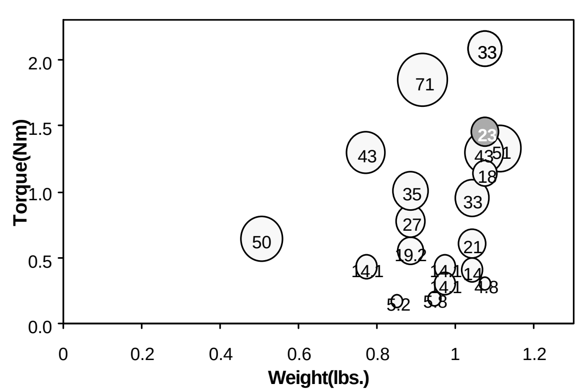

Figure 1: Geared Motor Comparison: Max Continuous Torque Vs. Weight Vs. Gear Ratio (gear ratio denoted by size of circles and numerical value)

2.2 Testing Device Design

The testing device included pliers with a grasping surface area of 103 mm^2 and lever arm lengths of 6.48 and 3.54 cm for handle and grasping finger loops respectively. These dimensions were chosen to approximate the equivalent dimensions of a typical endoscopic tool (Fig. 2). One finger loop was attached directly to the stationary based and the second finger-loop was attached to the base trough a shaft and a ball bearing. The modular design of the device allowed the use of a variety of shafted loads including a geared motor and a flywheel (Fig. 3). The adjustable flywheel was designed to match the reflected inertia of the motor shaft through the gear head.

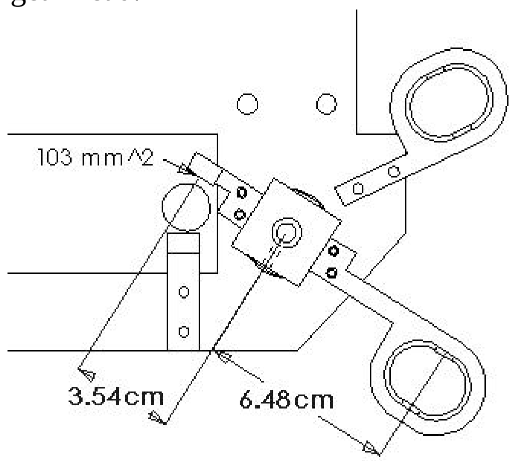

Figure 2: Top View of the Device Palpating a Silicone Rubber Sample

(a) (b) (c)

Figure 3: Different Configurations of Testing Device: (a) Geared motor (b) Flywheel (c) Control

2.3 Silicone Rubber Samples

Six silicone rubber materials were used as part of the experimental protocol. The Silicone materials compliance characteristics were controlled by the percentage (weight) of catalyst used during manufacturing. All the Silicone materials were shaped as a cylinder with a diameter of 14.7 mm and a length of 150 mm with the same color and texture. A detailed description of the mechanical properties of these materials was reported in [3]. In general the materials had an exponential stress-compression ratio under uniaxial compression (Eq. 1) conditions with an a and b parameters similar to soft tissue (Eq. 1)

$$K(l) = \frac{dT}{dl} = ab\,e^{a(1-l)} \quad (1)$$

where a and b are the material parameters, l is the compression length-ratio, T is the uniaxial compression stress, and K is the material stiffness.

The six silicone rubber samples were evenly graded as measured by stress length-ratio characteristics; this makes them ideal for the purpose of the subjective testing experiment.

2.4 Experimental Protocol

The experimental protocol included six blindfolded subjects that were asked to rank the stiffness of silicone rubber samples using three testing devices. The experimental protocol included two step: (1) for each testing device the subject first used the testing device to palpate each sample in order from 1 to 6 (2) The subject was then blindfolded and randomly presented all 30 possible permutations of sample pairs. For each pairing, each subject was allowed to palpate the first silicone sample with out any time limit. The subject was then allowed to palpate the second sample of the pair until he or she decided which sample was stiffer. The time of palpation for the first and second sample along with the choice for the stiffer sample were recorded for each permutation. The protocol was repeated three times using three testing methods: (1) the device with the motor (inertia and friction); (2) the device with the flywheel (matched inertia), and (3) the device alone (control). The order of methods was varied for each of the six subjects in order to eliminate biasing. Due to experimental setup and the ability of a user to subjectively sense what method was being used, it was not possible to blind the subjects or the testers from knowledge of the method being tested.

2.4 Analysis

In the analysis of the experimental data, a number of variables were chosen as potentially indicative of discernability; these included the following.

- **Error Score (ES)-** For each permutation, if the pair was incorrectly discriminated, an error score was assigned according to the numerical difference in the samples. For example, an incorrect discrimination of sample 5 and sample 2 would receive an error score of 3. If no mistake was made an error score of zero was assigned.
- **Total Palpation Time (TPT)-** This is the sum of the first and second squeezing time for each permutation. A longer total palpation time might indicate a greater difficulty in palpation as well as an increased difficulty in discriminating between a pair of samples.
- **Second Palpation Time (SPT)-** This is the time that the subject spent manipulating the second sample. If a subject spends an extended period of time squeezing the second sample, the SPT might be an indicator of discrimination difficulty.
- **Time Ratio (TR)-** This is the second palpation time divided by the first palpation time. The use of this statistic is intended to eliminate the time variations of different squeezing techniques. A smaller ratio might indicate easier sample discrimination.

By comparing the first, second, and third methods tested, these variables were analyzed to determine if any learning had occurred. Specifically, one-factor analysis of variance (ANOVA) was utilized to determine if learning effects might be present in the ES, TPT, SPT, and TR.

In a similar fashion, ANOVA was utilized to determine whether the type of method (Control, Flywheel, or Motor) had a significant effect on ES, TPT, SPT, and TR. In general, a one-factor ANOVA test was used, but in some cases a two-way ANOVA was performed as well to determine if a difference existed between the subjects. Furthermore, in cases where ANOVA indicated significant differences among means, Scheffe's Method for post hoc analysis was utilized to determine which means were different.

3. Results

3.1 Minimal Learning Effect

When the first, second, and third methods were compared using a single-factor ANOVA, there was no significant difference between the mean of the error scores. In fact, ANOVA showed that none of the variables observed (ES, TPT, SPT, TR) were affected by learning from method to method. Furthermore, a comparison of error score versus trial number indicates that no noticeable learning can be seen both within each method and between the methods.

3.2 Negligible Method Type Effect

In general, subjects were able to discriminate the samples equally well regardless of testing method type (Fig. 4). The overall discrimination success rate was 84 %, with the control, flywheel, and motor having success rates of 83%, 86%, and 84% respectively. ANOVA demonstrated that the method type had no significance for error score or time ratio (See Fig. 4). However, the analysis did reveal that TPT and SPT were both significantly effected by the testing method (p = .002 and p = .03 respectively). Further analysis with Scheffe's method showed that, in both cases, the mean palpation time of the control method was significantly ($a < 0.05$) less than for the other two methods.

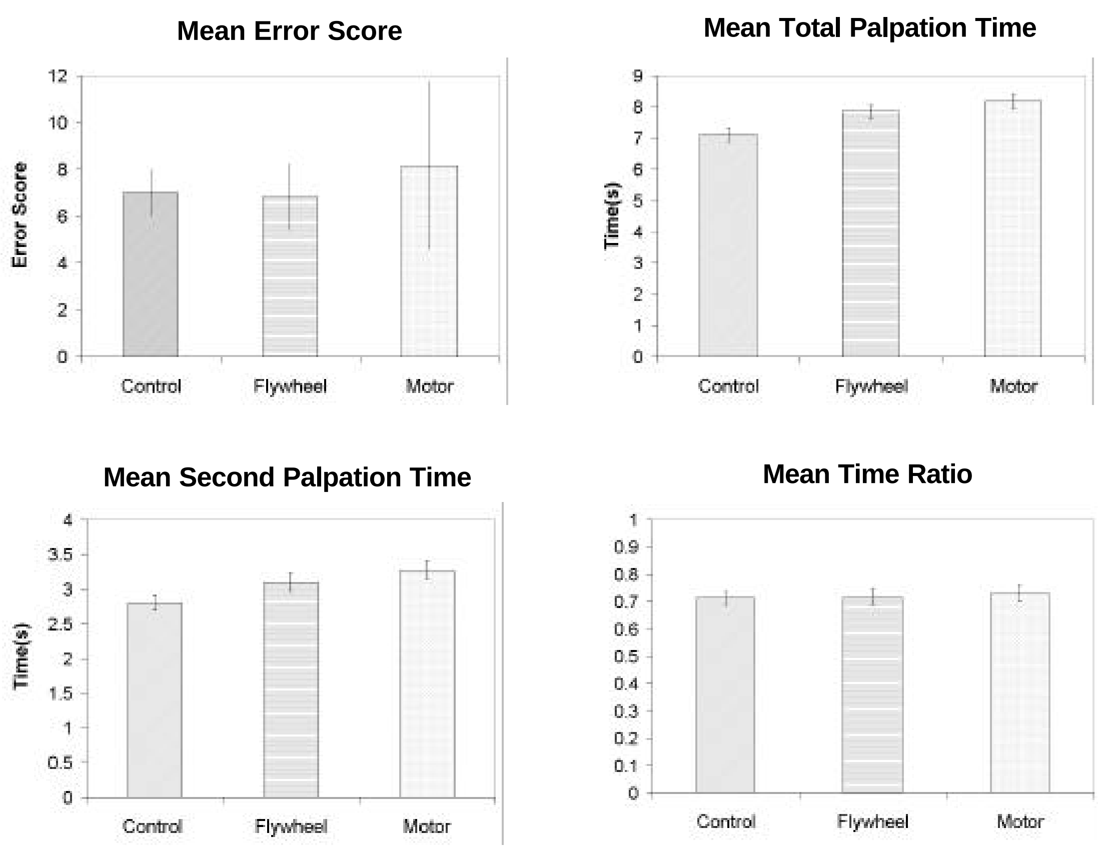

Figure 4: Summary of Variation in Experimental Variables across Method Type

3.3 Significant Difference Among Subjects

A two-way ANOVA revealed that error scores were significantly different for each subject and that a significant interaction existed between the subject and the testing methods. In fact, similar results were seen with the remaining variables (TPT,SPT,RT). Though, in general, low correlation existed between variables, it was found that subjects who spent less time palpating generally had a lower error score ($r^2 = .57$). A comparison of the normalized experimental variables for each subject is included in Figure 5.

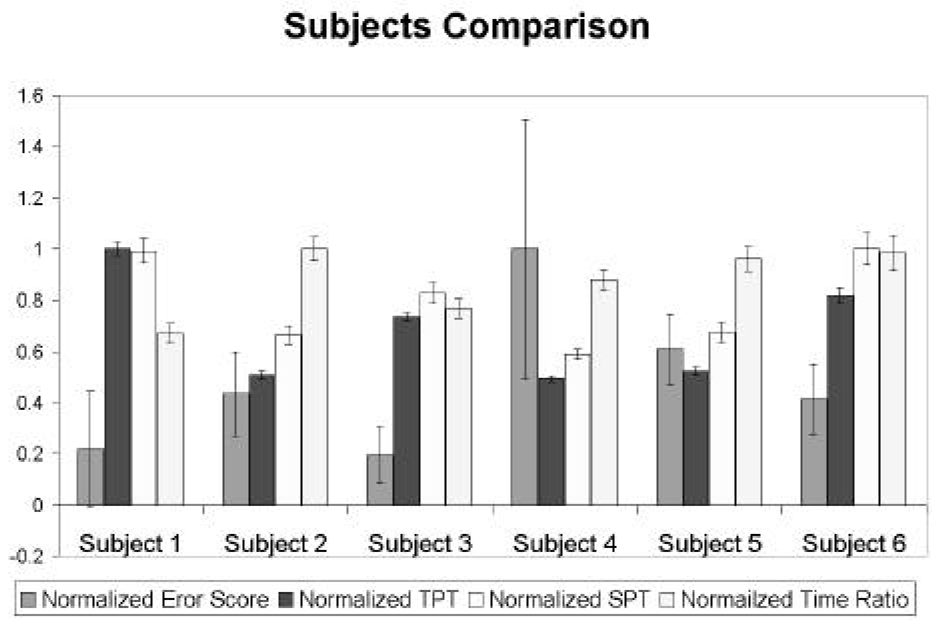

Figure 5: Comparison of Variables across Subject Pool

3.4 Subjective Observations

Although no specific instructions were given as to how the subjects should palpate the tissue, many of the subjects adopted a similar technique. Rate and accuracy varied greatly from subject to subject, however all subjects would generally palpate each sample repetitively. Most subjects would accelerate the pliers to a closed position and then hold it temporarily stationary before returning to an open position. For the cases where mechanical loads were present, subjects were observed to expend more effort in opening and closing the pliers.

4. Discussion and Conclusions

Many of the findings of this experiment were unexpected. Subjects were able to discriminate between the stiffness of the sample pairs more accurately than had been expected. Furthermore, none of the test variables demonstrated any significant difference between the flywheel and motor in perceiving the stiffness of the tested materials. Nevertheless, a number of potentially valuable conclusions may be drawn from this experiment.

As the method was varied between the control, flywheel, and motor, neither the error score nor discrimination percentage indicated any significant difference in a subject's ability to correctly discriminate the stiffness of the sample pairs. Thus, it appears that the motor characteristics of the geared motor chosen for this experiment were not able to significantly impair stiffness perception. If one considers a simplified model for the forces being applied during palpation, these findings make intuitive sense. The forces felt by the subject are described by the following relationship:

$$M = I\ddot{q} + B\dot{q} + K(q) \tag{2}$$

where q is the angular position of the pliers, $K(q)$ is a moment related to the deflection of the sample, B is proportional to the friction in the shaft, I represents the inertia of the device, and M is the moment experienced by the subject. When squeezing, most subjects would squeeze the silicone rubber to a certain point and then hold the pliers relatively stable. In this quasi-static state, the angular velocity and acceleration become less significant. Thus, it makes sense that in most of the experiments, subjects were able to sense tissue stiffness regardless of the motors friction and inertia.

In analyzing all of the experimental metrics, only the palpation time (both SPT and TPT) of the control was significantly less than the palpation time for the flywheel and motor. Certainly, as closing and opening involve both angular velocity and acceleration, the time and energy needed to repetitively palpate a tissue increase with friction and inertia. Thus, this slight but significant increase in palpation time for the flywheel and motor methods may be a result of this phenomenon.

In conclusion, it appears that the perception of stiffness is not significantly effected by the mechanical characteristics of the geared motor chosen for this experiment, but these characteristics may effect the time and energy exertion necessary for tissue palpation. Thus, although it may be possible to consider geared motors for use in haptic surgical devices, other factors, such as user fatigue and speed require consideration.

5. Acknowledgements

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