Human Performance in a Knob-Turning Task

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Abstract

Knob turning is a common task that should influence the design of human-machine interfaces such as prosthetic arms, teleoperated robots, and virtual environments. This study examines the following metrics for a specified knob rotation: turning strategy, including arm motions used and number of grasps made, time used to complete the motion, and maximum applied forces and torques. The subjects' task was to rotate a one-degree-of freedom haptic knob at least 270 degrees for two angles of attack (hand parallel versus perpendicular to the plane of the knob), three knob sizes, and three motor gains. Results on the initial 260 degrees of rotation show that a more distal arm motion is used for a parallel angle of attack, decreased knob size, and increased gain. Further, a change in the angle of attack affects each metric, with the exception of the maximum z-axis force and the maximum lateral torque. A variation in the knob size modulates each metric, with the exception of the maximum z-axis torque and the maximum lateral force. A modification of the motor gain influences the outcomes of all of the metrics.

1. Introduction

In daily life, a person frequently encounters knob-turning tasks such as rotating a doorknob to enter a room, twisting the lid of a peanut butter jar to open it, or spinning the knob of a stereo system to change the volume of music. Although interacting with knobs may be a simple task for humans to perform, the ability to manipulate these knobs is not as easily accomplished by a robot or human-machine system. There are many different variables that can describe a knob (e.g. size, shape, damping), and the human strategy for turning the knob can vary widely (e.g. *angle of attack*: manipulating the knob with one's hand perpendicular versus parallel to the planar surface of the knob).

An understanding of how humans interact with knobs can be beneficial in the design of human-machine interfaces such as teleoperated robots, prosthetic arms, and virtual environments. Prosthetic arms should be intuitive to the user and, at the same time, appear human-like. A study by Atkins, et al. [2] found that users of upper-limb prostheses ranked wrist dexterity as a necessary feature in future designs. These wrist motions include the ability to move the hand side-to-side (wrist adduction/abduction), to rotate the hand (wrist circumduction), and to move the hand up and down (wrist pronation/supination). Identifying knob-turning behaviors such as arm/finger motion/duration and applied forces and torques, will aid in the design of teleoperation systems and virtual environments by guiding the selection of the number of actuators, placement locations, and actuator properties (e.g. torque output capability).

Researchers in the area of knob turning have investigated human behavior and performance. Romilly et al. [8] conducted a survey that defined knob turning as a task desired by potential orthotics users, and presented the arm motions used during a knob-turning task. Work done by Novak et al. [7] provided the kinematics of subjects during the task of knob turning. Hasser and Cutkosky [4] developed a model of the hand's dynamics during the task of holding a knob using a specified grasp style and varying grip forces.

Researchers have also investigated the human's applied forces and torques when the properties of the knob, such as shapes, sizes, and textures, are varied. Crawford et al. [3] explored the effects of knob shape, surface area, and human size and weight on applied torque. Imrhan and Loo [5] showed that in the elderly, for both smooth and rough textured knobs of diameters 31, 55, and 74mm, applied torque linearly increases with knob diameter.

Impedance-controlled haptic knobs (e.g., [1], [6], [9]) have been developed and used to create new haptic applications or perform psychophysical studies.

This study provides new data on the number of grasps used to rotate a knob through a prescribed angle, the time

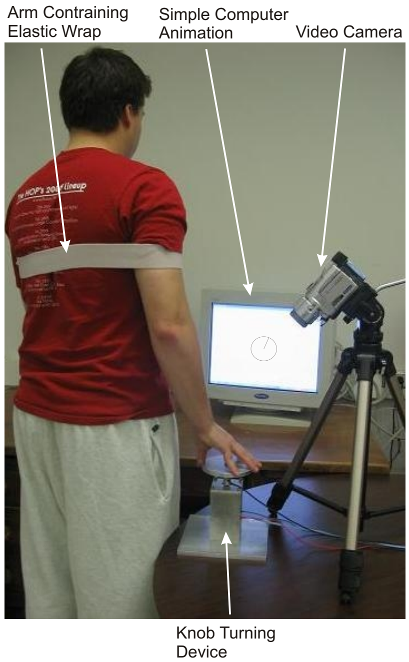

Figure 1. Apparatus for the knob-turning experiment.

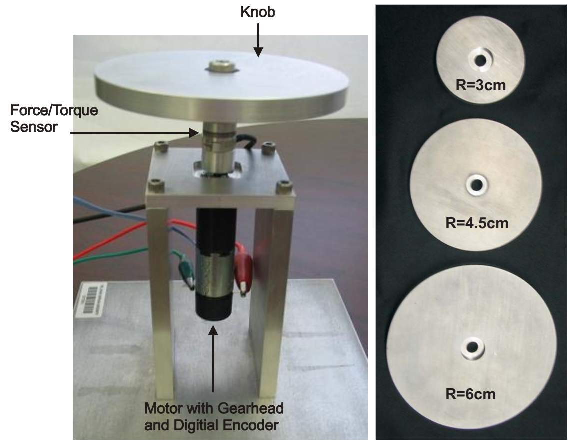

Figure 2. (Left) A one-degree-of-freedom motorized knob with force/torque sensor. (Right) Three knob sizes with corresponding radii, R.

needed to complete the rotation, and the amount of force and torque applied to the knob when the angle of attack, knob size, and motor gain are varied. In addition, we extend the work of other researchers by providing further classifications of which arm motions are used for specific properties of the knob.

2 Experimental Procedure

2.1 Apparatus

The experimental apparatus consists of a knob-turning device with associated control computer and circuitry, a visual display of the knob position on a computer screen, a video camera to record the user's motion, and an elastic strap to constrain the user's arm (Fig. 1). The knob-turning device is a one-degree-of freedom robot, as shown in Fig. 2. It features a Maxon A-max 22 DC motor with a 128:1 gearhead and digital encoder with a 0.007 degree resolution. An ATI Nano-17 6-axis force/torque sensor couples the motor's output shaft to a knob. Three knobs of varying radii (3cm, 4.5cm, and 6cm) are used in this experiment (Fig. 2). The knobs are 1 cm thick aluminum cylinders. The motor's encoder records the motion of the knob, and the force/torque sensor measures the subject's applied forces and torques. The video camera collects video recordings of each subject's hand motions for all trials.

The following control law was implemented to govern the motion of the knob:

$$\omega_d = k_a \tau_z \tag{1}$$

where ω_d is the desired angular velocity of the knob computed from a motor gain, k_a, and torque, τ_z, the subject applies about the axis of the motor. The motor gains used in this experiment are $k_a = 0.0001$, 50, and 350 deg/Nmm-s. These values were chosen to make the knob appear respectively difficult, medium, and easy to turn according to the experimenter's qualitative assessment.

The low-level controller to output the motor torque, τ_m, was:

$$\tau_m = k_p \omega_d \Delta t + k_d(\omega_d - \omega_a), \tag{2}$$

where Δt is 1 ms, ω_a is the actual (measured) angular velocity, and the gains are $k_p = 87.2$ Nmm/deg and $k_d = 0.0218$ Nmm/deg-s.

2.2 Methods

The study included 6 male and 4 female right-handed, healthy subjects of ages ranging from 20 to 30. No subject reported a neurological illness or physical injury that would impair hand performance.

The subjects' hand size was defined as the distance from the subject's wrist to the distal end of the middle finger, and ranged from 16.5cm to 20cm. Subjects' self-reported experience with virtual environments spanned from "none" to "very experienced".

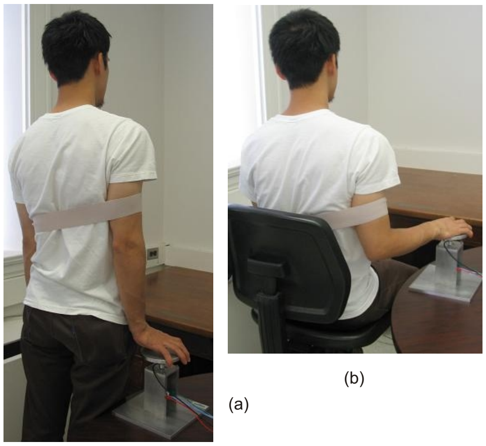

Figure 3. Subject position for two different angles of attack relative to the plane of the knob surface: (a) perpendicular (b) parallel

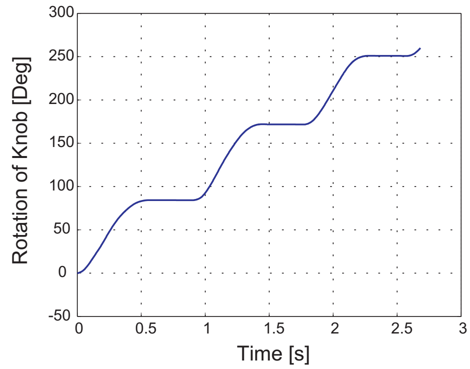

Figure 4. Example data for angular position of the knob. The subject is under the condition of a perpendicular angle of attack, with knob radius $R = 6$ cm, and motor gain $k_a = 350$ deg/Nmm-s. In this example, the subject reached approximately 270 degrees and then stopped.

The experiment lasted approximately one-half hour for each subject. After hand measurements were made, the subject's right elbow was held against the torso with an elastic strap. This constrained the motion of the subject's right arm to only motions of the forearm, wrist, and fingers (Fig. 1). Motions of the shoulder and torso were inhibited, as well.

During the experiments, the subjects were placed in two positions: standing on a footstool and sitting in a chair (Fig. 3). Each position corresponded to a different "angle of attack" of the arm relative to the knob. When standing, the subject's right arm was straight and *perpendicular* to the planar surface of the knob. When sitting, the subject's right arm was bent 90 degrees at the elbow with the forearm *parallel* to the planar surface of the knob. Additionally, the height of the footstool and chair were adjusted so that each subject could comfortably and naturally turn the knob.

Once the equipment was set up, the subject was instructed to use only the right hand to turn the knob clockwise at least 270 degrees using only wrist and finger motions. We chose 270 degrees because we were interested in one's arm turning behavior when only several grasps of the knob were completed; from initial observations, we found that 270 degrees allowed for numerous grasps. The rotation of the knob was relayed to the subject as a simple animation of the knob's current position, displayed on the computer screen (Fig. 1). No limit was placed on the time to complete the task.

Before data collection began, each subject was permitted to practice turning the knob with a randomly selected size and angle of attack for each of the three motor gains, in order to become comfortable interacting with the system. Once each trial was completed, the subject released the knob and raised his or her right hand. The experimenter then returned the system to the initial $\theta = 0$ degrees position to prepare for the subsequent trial.

Two trials were conducted for every combination of knob size, motor gain, and angle of attack. This resulted in a total of 36 trials per subject. The combinations of experimental parameters were varied using the following procedure. First, a random angle of attack was selected. Then, a random knob size was set. Finally, a random motor gain was specified. Before the knob size was changed, all motor gains were tested in random order. Similarly, before the angle of attack was varied, all three knob sizes were used in random order. This grouping of conditions minimized experimental set up time, yet maintained a unique order of conditions presented to each subject.

3 Results

Our data analysis examines knob-turning strategy, including arm motions and number of re-grasps during knob turning, the time taken to achieve the prescribed amount of rotation, and the amount of applied force and torque for experimental conditions using combinations of three knob sizes, three motor gains, and two angles of attack. Fig. 4 presents an example plot of a subject's angular position as a function of time. Since the subjects had very different motions near the end of the knob rotation, our analysis was conducted on only the first 260 degrees of the knob rotation.

Condition		Finger Movements	Wrist Adduction and Abduction	Wrist Circumduction	Elbow Pronation and Supination
Angle of Attack	Parallel	45%	55%	0%	0%
	Perpendicular	63%	0%	5%	32%
Knob Radius (cm)	3	68%	9%	1%	12%
	4.5	65%	23%	0%	12
	6	29%	40%	8%	23%
k_a (deg/Nmm-s)	0.0001	42%	36%	2%	20%
	50	46%	32%	2%	20%
	350	74%	15%	3%	8%

Table 1. Arm motions used while turning the knob.

3.1 Turning Strategies

Based on observations of the videos recorded during the experiments, we have classified four primary arm motions used when turning a knob: *finger movements*, *elbow pronation/supination* (rotation along axis that is aligned with the forearm), *wrist adduction/abduction* (motion that pulls hand towards or away from the midline of the wrist), *wrist circumduction* (a combination of wrist flexion/extension and adduction/abduction) which appears as a rotary motion.

The video recordings of all trials were subjectively evaluated by the experimenter and defined by one or a combination of several of these motions. The entries of Table 1 are the percentages of trials in which subjects used the specified arm motion more than any other arm motion, for the various experimental conditions. Note that these results display only the most heavily used motion, although in many trials the subjects used a combination of two and, at times, three different arm motions.

In addition to the general arm motions used by the subjects, we identified the number of grasps used to turn the knob through a specified angle. This signifies how many times the subject readjusts his or her hand in order to complete the desired knob rotation. The means and standard deviations for the number of grasps subjects made are shown in Fig. 5. For the main factors, a 3-way Analysis of Variance (ANOVA) revealed that the number of grasps is a function of the angle of attack ($p = 0.000$, $F(1, 342) = 106.012$, $\eta_P^2 = 0.237$), motor gain ($p = 0.000$, $F(2, 342) = 32.371$, $\eta_P^2 = 0.159$), and knob size ($p = 0.028$, $F(2, 342) = 3.606$, $\eta_P^2 = 0.021$). Interaction effects were not significant in any interactions except that between the angle of attack and motor gain ($p = 0.006$, $F(2, 342) = 5.254$, $\eta_P^2 = 0.030$. Pairwise comparisons using Tukey's method showed that all comparisons within each condition type had means that were statistically different from the others. Lines in the plot with stars above the pair of two groups describe cases where the means are statistically different.

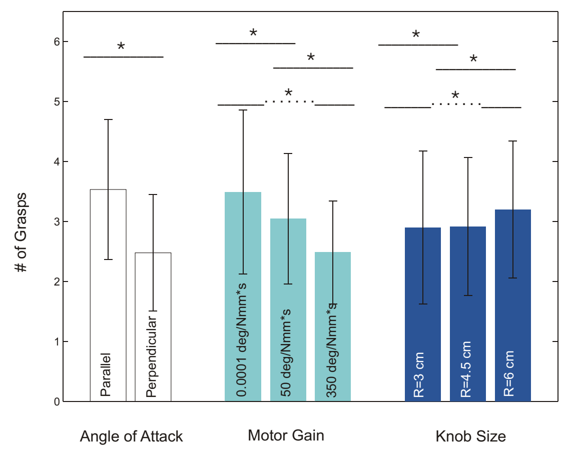

Figure 5. Number of grasps of knob in a 260 degree knob rotation. Lines with stars above connect conditions in which the means are statistically significantly different.

3.2 Duration of Knob Rotation

The time the subjects used to rotate the knob was also tested. The means and standard deviations for the time used are plotted in Fig. 6. For the main factors, a 3-way ANOVA revealed that time is a function individually of the angle of attack ($p = 0.000$, $F(1, 342) = 24.358$, $\eta_P^2 = 0.067$) and motor gain ($p = 0.000$, $F(2, 342) = 51.195$, $\eta_P^2 = 0.230$), but not for knob size ($p = 0.727$, $F(2, 342) = 0.3195$, $\eta_P^2 = 0.002$). All interaction effects were not statistically significant. Pairwise comparison of the knob size using Tukey's method showed that there are statistically significant differences in the means between the two angles of

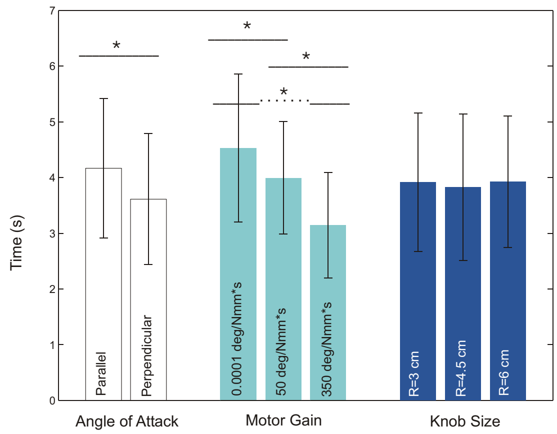

Figure 6. Time used to completely turn the knob 260 degrees. Lines with stars above connect conditions in which the means are statistically significantly different.

attack and between each pair of the three motor gains.

3.3 Applied Forces and Torques

We collected the maximum z-axis forces, lateral forces (magnitude of forces applied in the x-y plane), z-axis torques, and lateral torques (magnitude of torques applied about axes in the x-y plane) applied by each subject. Lateral forces and torques were calculated as $\sqrt{f_x^2 + f_y^2}$ and $\sqrt{\tau_x^2 + \tau_y^2}$, respectively where x indicates a motion about the x-axis, y about the y-axis, f indicates a force, and τ a torque. The means and standard deviations for these results, along with the results of pairwise comparisons for statistically significant differences, are plotted in Figs. 7 and 8. Further, pairwise comparisons as determined using Tukey's method, are presented as lines in the plot with stars above the pair of two groups describe cases where the means are statistically different.

For the main factors, a 3-way ANOVA revealed that the force along the z-axis is not statistically significant for the angle of attack ($p = 0.433$, $F(1, 342) = 0.615$, $\eta_P^2 = 0.002$), but is dependent on the motor gain ($p = 0.000$, $F(2, 342) = 20.502$, $\eta_P^2 = 0.107$) and knob size ($p = 0.004$, $F(2, 342) = 5.760$, $\eta_P^2 = 0.033$). All interaction effects were not statistically significant.

For the main factors, a 3-way ANOVA showed that lateral force is dependent upon the angle of attack ($p = 0.010$, $F(1, 342) = 6.670$, $\eta_P^2 = 0.019$) and motor gain ($p = 0.000$, $F(2, 342) = 134.258$, $\eta_P^2 = 0.440$), but not statistically significant for the knob sizes ($p = 0.076$, $F(2, 342) = 2.602$, $\eta_P^2 = 0.015$). All interaction effects were not statistically significant.

For the main factors, a 3-way ANOVA revealed that the torque along the z-axis is dependent on the angle of attack ($p = 0.000$, $F(1, 342) = 45.388$, $\eta_P^2 = 0.117$) and motor gain ($p = 0.000$, $F(2, 342) = 10.594$, $\eta_P^2 = 0.058$), but not statistically significant for the knob size ($p = 0.191$, $F(2, 342) = 1.663$, $\eta_P^2 = 0.010$). All interaction effects were not statistically significant.

For the main factors, a 3-way ANOVA showed that lateral torque is dependent on the angle of attack ($p = 0.048$, $F(1, 342) = 3.953$, $\eta_P^2 = 0.011$), motor gain ($p = 0.000$, $F(2, 342) = 69.194$, $\eta_P^2 = 0.288$), and knob size ($p = 0.001$, $F(2, 342) = 7.402$, $\eta_P^2 = 0.042$). All interaction effects were not statistically significant.

4 Discussion

This study provides general data about human performance during the task of turning a knob. We tested the effects of changing the angle of attack, knob size, and motor gain on the metrics being analyzed. The metrics are the arm motion that is implemented when turning a knob, the number of grasps needed to rotate the knob a prescribed amount, the total time used to achieve this prescribed amount of rotation, and the amount of applied force and torque.

4.1 Turning Strategy Trends

Our work confirms and builds upon that of Romilly et al. [8]. In both studies, the identified arm motions utilized in turning a knob included a forearm rotation, wrist flexion, and wrist yaw. Our models differ, however, in that our study restricts shoulder motions and identifies finger motions as a movement, whereas Romilly et al. 's study includes the shoulder motions but does not identify the finger motions.

Observation of human subjects' arm movements found that they tended towards a more distal motion for a parallel angle of attack in comparison to a perpendicular angle of attack. When one approaches a knob with a parallel angle of attack, using the forearm is not effective, since this motion would not allow rotation of the knob in the appropriate direction. However, when one approaches a knob with a perpendicular angle of attack, wrist movement is not the primary motion. Rather, pronation and supination of the elbow are used. This may extend to the idea of when one opens a jar that requires a large initial torque, the person gets "on top" of the knob and uses the entire forearm to twist open the lid.

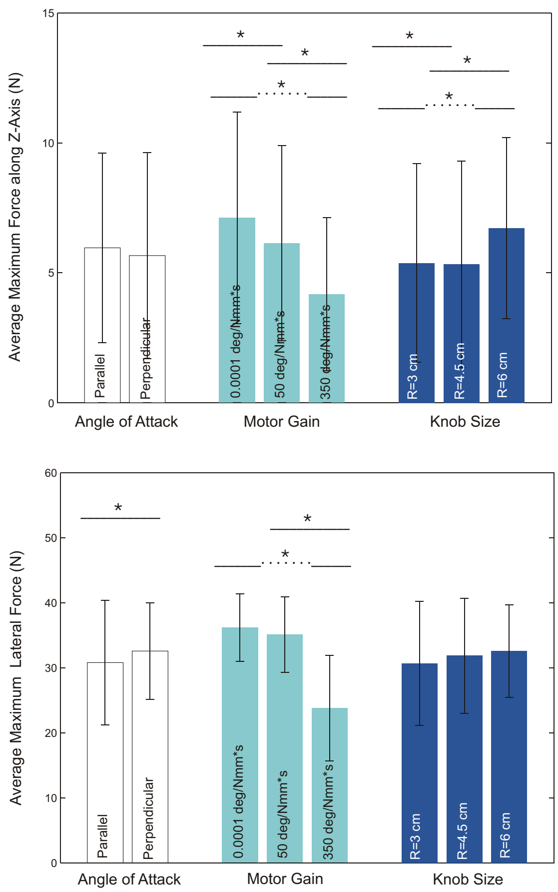

Figure 7. The average of the extrema of the forces along the z-axis and lateral force axis in 260 degrees of rotation. Lines with stars above connect conditions in which the means are statistically significantly different.

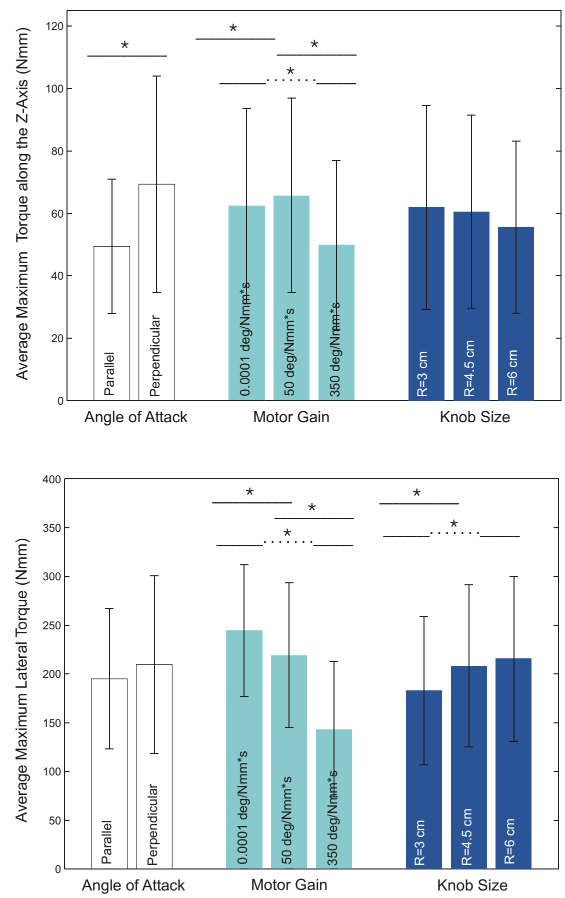

Figure 8. The average of the extrema of the torques along the z-axis and lateral torque axis in 260 degrees of rotation. Lines with stars above connect conditions in which the means are statistically significantly different.

As knob size increases, the subjects tend toward more proximal motions. This is intuitive, since, as objects become smaller, a more dexterous hand manipulation is needed. Finger movements are able to provide more dexterous motions than those of the wrist or arm.

An increase in the motor gain value tends towards a more distal arm motion as well. An increased gain value results in less required torque to achieve the same angular velocity of the knob, as expressed by Equation 1. This rides on the same idea of opening a jar that requires a large initial torque by getting "on top" of the knob and using the entire forearm.

In the example plot of a subject's angular position as a function of time (Fig. 4) it is possible to determine the number of grasps the subject makes by noting the breaks in the slopes. This data also reveals the amount of rotation for each grasp, and the time it takes between each grasp of the knob. Fig. 5 revealed that changing the knob's radius, motor gain, and the angle of attack will influence the number of grasps that the human makes. A perpendicular angle of attack, larger knob size, and smaller motor gain results in an increase in the number of grasps.

4.2 Quantitative Result Trends

The amount of time it takes to turn a knob a specified amount is dependent upon the angle of attack and motor gain, but statistical significance was not found for dependence on the knob size. A parallel angle of attack and lower motor gain resulted in a slower motion. As noted from the number of grasps, both of these factors also require a larger number of grasps so intuitively it follows that they would require a larger amount of time to complete the motion. However, this does not follow for the knob size.

Analysis of the forces and torques applied to the knob shows the average lateral forces to be larger than the average maximum forces along the z-axis. Likewise, the applied torques by the human to the system were higher in the lateral direction than those about the z-axis, by a factor of approximately 3. Both the average maximum force along the z-axis and the average lateral maximum torque were found to be dependent upon the chosen motor gain and knob size, whereas both the average maximum torque along the z-axis and the average maximum lateral force were found to be dependent upon the angle of attack and motor gain. In general, the data shows that the human is applying a significant amount of force and torque in directions that do not directly serve to rotate the knob. With different arm positions or constraints, we might observe a more efficient knob-turning behavior.

The findings presented in this paper can be applied to prosthetic arm designs so that the arm's movements will appear more human-like. In addition, implementing the findings in the design of virtual environments and teleoperation systems can make the human-machine interaction more intuitive and user-friendly.

Acknowledgments

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