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Feasibility Study of a Wearable Haptic knob System

Junji Sone[a*], Yuta Tamura[b], Shougo Ueda[c], Hideki Iwai[d], Kinya Fujitz[e]

[a,b,c]*Department of applied computer science, Tokyo Polytechnic University, Iiyama, 1583, Kanagawa 243-0297 Japan*

[d]*Graduate school of Engineering of Tokyo Polytechnic University, Iiyama, 1583, Kanagawa 243-0297 Japan*

[e]*Graduate School of Tokyo University of Agriculture and Technology 2-24-16 Naka-cho, Koganei-shi, Tokyo, 184-8588, Japan*

[a]*Email: sone@cs.t-kougei.ac.jp*

[e]*Email: kfujita@cc.tuat.ac.jp*

Abstract

In this study, we develop an event-based wearable haptic knob system that can be used in three-dimensional space. The first step involves building custom-built brakes and attaching them to a human forearm to achieve a wearable haptic knob. The display is built using a carbon-fiber frame. As our system is experiment-based, target torque curves are collected by a force sensor before using the torque representation. We confirm the effectiveness of our developed display through three operations, namely doorknob rotation, valve closing, and valve opening by the test subject. In the first step, the rotational axis was fixed on a table. These results are then used to develop the perfect wearable haptic system that includes a rotational axis in the display.

Keywords: Haptic knob; Wearable; haptic device; Torque sensation; Virtual Reality.

1. Introduction

Haptic information is important for interactive manipulation of virtual objects and for enhancing the presence of virtual environments. A number of haptic interface devices [1] that exhibit reaction force or tactile sense by touching objects are reported in the literature [2,3,4]. Hasser and his colleagues built a rotational model of a hand by identifying the system parameterization of a haptic knob [5]. Swindells and his colleagues acquired several parameters of a haptic knob such as relative inertia, friction, detent strength, and detent spacing. They succeeded in sensing the torque of a volume and rotary switch using a motor [6].

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* Corresponding author.

However, they did not consider the high inertia and high amplitude in the case of closed-valve operation. Lambercy and his colleagues developed a two-degree-of-freedom haptic knob display that can execute handshakes and rotation and can be used for rehabilitation of these [7]. They used torque generation with velocity-dependent and position-based methods. Chapuis and his colleagues considered a new type of haptic knob system using a motor, brake, and clutch, and succeeded in representing a simple spring and wall feeling [8]. Kikuchi and his colleagues developed a haptic display for rotational resistance in which the torque is controlled by an electric visco-elastic fluid [9].

Novak et. al. investigated the kinematics of a coordinated multijoint hand manipulation task[10]. Gurari and Okamura studied a specific knob rotation turning strategy, including components of arm motions used and number of grasps made, time used to complete the motion, and maximum applied forces and torques[11]. Their study examined the general task of wide-angle knob turning and multiple submovements. Our system, on the other hand, incorporates a one-turn action, which requires further research for future development of knob systems. We also used an electromagnetic brake as the actuator and developed a haptic knob for closing and opening a valve. During this process, the brake system was fixed to a table [12]. This system was very heavy and inflexible for free operation in the field because it was fixed to a table and used a commercial brake.

Many mobile phones display tactile and pseudo-haptic sensations by the use of piezoelectric materials and vibration motors[13]. These haptic sensations express the sense of touch, some alerts, and some impact shocks. CyberGraspe, used as a wearable device, can represent the actual grasp forces for each finger. The aim of our system is to realize the sense of wrist rotations by using a wearable device to generate real torque.

In this study, we develop a wearable haptic knob system that can be used in three-dimensional space. This system aims to assist development of evacuation drills in response to an earthquake and so on. We are also considering applying the virtual experiment to a virtual shop, exploring an unknown building like an adventure game. This study employed an evacuation drill, which involved the user wearing a head-mounted device showing our haptic display and walking around in a virtual space. This is also effective for some aspects of training for plant operations in rooms with many valves, such as a nuclear plant.

The first step is the constructing custom-built brakes and attaching them to a human forearm in order to realize the wearable haptic knob. In the second step, we design the haptic system, including the rotational axis and the fully wearable display. This paper reports on the first step of the development. We build the haptic knob frame, brake mechanism, and control system. The identification of the brake's characteristic properties is then carried out. The effectiveness of our device for knob sensation is then tested experimentally. Section 2 explains the configuration and mechanism of the haptic knob system and identifies various torques. Section 3 provides experimental verification of the developed system. Finally, Section 4 gives the conclusions.

2. Concept of virtual haptic knob

2.1. Requirements of a wearable haptic knob

Many knob-like devices, such as doorknobs, valves, bolts, dials, bottle caps, etc., use grasping and rotation operations. Therefore, we need to represent anti-torques for the outward rotational action of forearms in order to establish virtual sensations for these devices.

It is necessary that doors be located freely for virtual evacuation drills. Thus, these applications need a wide movable area. Therefore, it is necessary to establish a wearable haptic knob system for anti-torque sensation of the outward rotational action of forearms.

2.2. Specifications and outline of the design

Some researchers use motors to represent the anti-torques of rotational action. These devices are usually very heavy and it is difficult to develop a wearable system using them. Furthermore, they do not require active torque generation for the outward rotational action of forearms. However, they do require sufficient braking torque for their operation. Therefore, we use a brake system that is compact and has sufficient brake power and controllability.

It is also necessary that the device be lightweight to reduce a person’s load while operating and wearing it. Therefore, we set up the device on the forearm and used a string to transfer the anti-torque. This achieves a lightweight wearable haptic knob and improves the weight for the haptic sensation. The string is used to represent torque and produce a flexible and stable haptic knob, because the directions of operations change a person's posture and the dimensions of their body. Figure 1 shows the concept of the haptic knob. We aim to develop a wearable haptic knob and design a lightweight and high-torque system. A carbon-fiber frame is used to keep the weight low. We use a micro brake with a high brake torque (1.2 Nm) to realize a variety of knob sensations. The wiring of the string was designed to generate sufficient torque and to avoid interference between the wrist and the string.

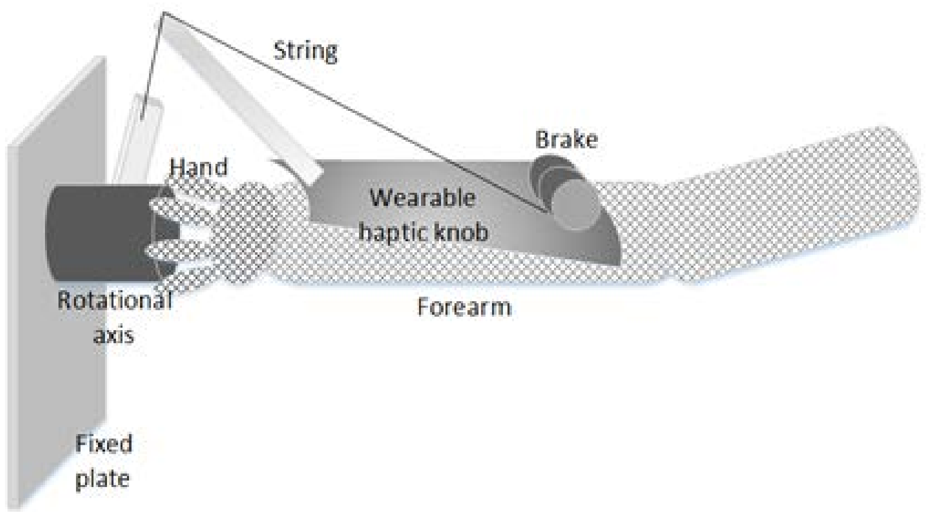


Figure 1: Concept of haptic knob

3. Configuration of the haptic knob

3.1. System overview

Figure 2 gives an overview of our haptic knob system. A knob was fixed to the table and ball bearings were used to ensure its smooth rotation. The knob was cylindrical in shape and the size (50 mm in diameter) was selected for ease of handling. The torque generation part was attached to the forearm with a carbon-fiber frame (120 mg) to make the system wearable. Rubber bands were fixed at two points to ensure free rotation of the wrist. The fixing cover of our device has a large surface area and rounded shape. The large cover was fitted to the upper part of the forearm using a wide rubber band, which was not fixed tightly to avoid discomfort during wearing.

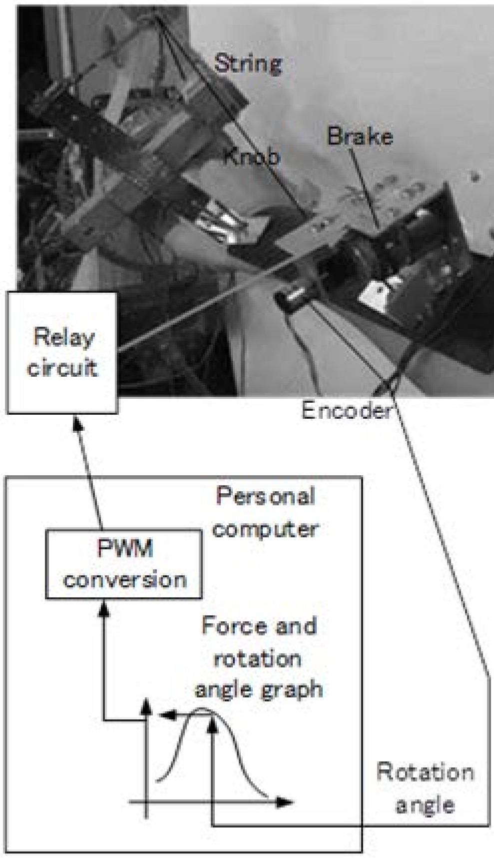


Figure 2: Haptic system configuration

Our system is an experimental system [14,15,16], in which we first measure the torque data for the cases of valve opening, valve closing, and doorknob rotation using a hand-made, parallel-plate force sensor [17] in which force is sensed by strain gauges. The relation between torque and the output voltage of the sensor amplifier was calibrated in advance.

The data for the three operations (valve opening, valve closing, and doorknob rotation) were saved in a personal computer as a reference table for targeted torque. Representative values of torque were obtained from the rotation angle of the subject and the reference table, and the braking system was operated by following the targeted torque curve.

3.2. Haptic knob system

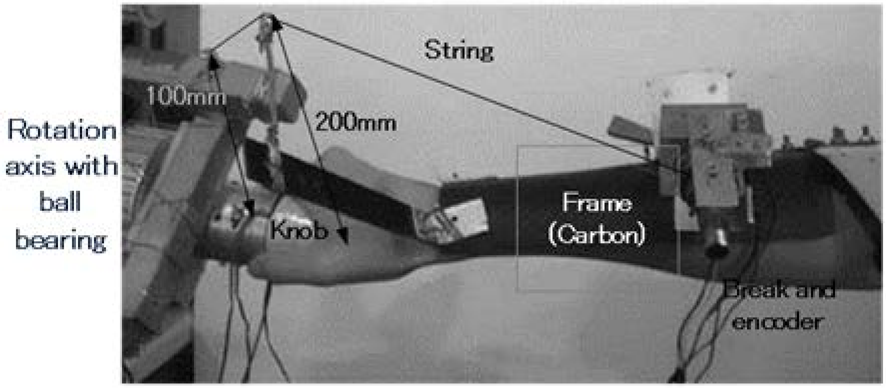


Figure 3: Wearable haptic mechanism.

One of the aims of the present study is to design a system that is wearable. However, it is difficult to establish a rotational axis in a wearable device. For this purpose, the rotational axis is set on a table using ball bearings.

Figure 3 shows the details of the haptic knob system. The carbon frame is fixed to the forearm to achieve a wearable design. Two electromagnetic brakes are fixed on a carbon frame at the elbow side. Brake torque is generated by the brake system and it represents the torque to the wrist through the string. The brake system consists of three component parts: an electromagnetic solenoid actuator (Miki Pulley Co. micro brake 112-04-13, 1.2 Nm), brake disks, and bobbins. A string is folded around the bobbin and connected to the wrist, similar to a SPIDAR[3]. We added a spiral spring to avoid the wires and wire reel loosening. In this case, the pull positions are set 200 mm from the center of the rotation axis to avoid interference between the wrist and the string. The string is fixed at an offset position of 100 mm at the knob center to produce a large torque. The total mass of the wearable haptic display is 420 g, at which the impact on a human arm is small.

The rotational angle of the wrist was measured by the encoder (Nidec RE12D-300 300P/R), which is driven by the string connected to the rotational axis. The representative torque is computed by the rotation angle and is defined in the reference table at every 10 ms. It is generated using pulse-width modulation (PWM). Average torque is controlled by the pulse width. We used a 24-V relay circuit and the pulse widths were controlled by a program written in the C language. Relations between pulse width and brake torque were measured before the experiment.

3.3. Identification of break and torque relation

In our system, force is generated by the friction of braking rotors, torque is generated by applying force at the

100-mm offset point and friction forces are controlled by the on–off ratio of PWM. The relationship between force and on–off ratio is then identified. We conducted free-fall experiments by changing the fall weight and by employing a wide range of torque values. The off time was fixed for weights of 150, 300, 500, and 700 g, and the on time was changed to identify the brake force by the brake system. In this study, the brake parameter was the On/Off ratio, and these combinations cannot decide one pair. We allowed some vibration of the brake to allow for inappropriate combinations. In a preliminary experiment, we searched for an appropriate combination for each weight, and used these parameters to identify the brake parameters.

The equation of motion for the free-fall experiment is given as:

$$ma = mg - \mu F \qquad (1)$$

Here a is acceleration, m is weight, g is acceleration due to gravity, y is position, and μF is friction force to represent the torque.

We solved this equation for position as follows:

$$y = \frac{mg - \mu F}{2m} t^2 \qquad (2)$$

$$Coe = \frac{mg - \mu F}{2m} \qquad (3)$$

where Coe is the quadratic coefficient. Therefore, μF can obtained from the following equation:

$$\mu F = mg\text{-}2mCoe \qquad (4)$$

To obtain the brake parameters, we conducted the free-fall experiment with a value of approximately 300 mm. First, we fixed the off time at 20 ms for 150 g, 15 ms for 300 g, 13 ms for 500 g, and 10 ms for 700 g. The relations between μF and the on-off ratio are found by this experiment and by using equation (4). The Coe is calculated from the quadratic fitting curve relating position and time.

Figure 4 shows the relationship between the on–off ratio and the representative force. On–off parameters were obtained at each section between 100 to 200 N, 200 to 300 N, 300 to 500 N, and 500 to 700 N. For these sections, the off time was kept fixed. In these sections, the relationship between on–off ratio and force is almost linear and we construct the approximation line using least-squares fitting. In this system, a representative torque is determined by applying the force on the rotational axis at an offset length of 100 mm.

4. Verification experiment

Figure 5 shows the configuration and dimensions of the haptic display. The knob is cylindrical in shape and a torque is applied at a point 100 mm from the center of the axis. As mentioned earlier, the force sensor is handmade and of the parallel-plate type. It senses force using strain gauges. The relationship between torque and output voltage of the sensor amplifier is calibrated in advance.

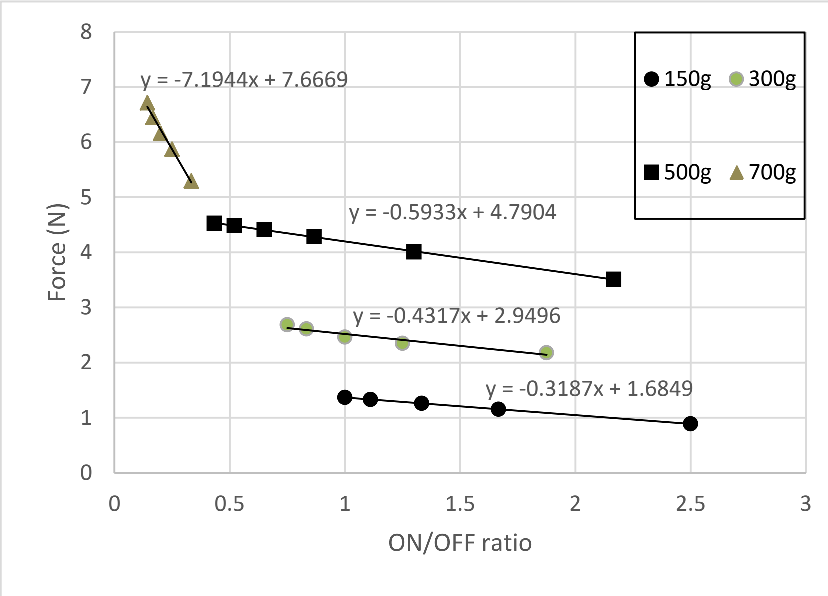


Figure 4: Relation between on-off ratio and represent force.

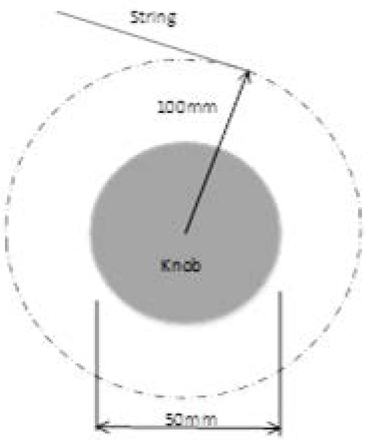


Figure 5: Configurational dimension of haptic display

We performed trial experiments. Experimental data for rotational angle and representative torque were acquired by the encoder and the force sensor and were saved to a personal computer.

Figure 6 shows the experimental configuration. The wearable haptic device was attached to the forearm of the subject with a rubber band. The effectiveness of the display was verified by ten people. The experimental tasks were rotation of a doorknob (RD), closing a value (VC), and opening a valve (VO).

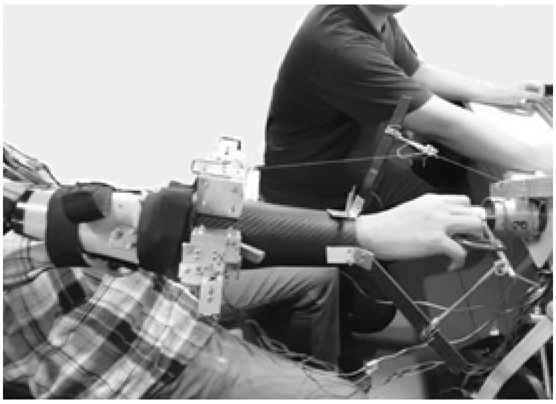


Figure 6: Experimental configuration. (Torque measurement configuration) display

Instructions to volunteer subjects were as follows:

1) Rotate the actual device.

2) Execute the haptic device using the same rotational action as for the actual device.

3) Evaluate the recognition level of torque (RLT) of the haptic device compared with the actual device using a five-step evaluation method.

4) Evaluate the authenticity of the represented torque (ART) of the haptic device compared with the actual device using a five-step evaluation method.

We permitted two to five trials for users to familiarize themselves with the experiment. A 5-level evaluation was used in which 5 means good and 1 means poor. In this experiment, one subject repeatedly compared the actual device five times. We used actual doorknobs and valves. We also measured the representative torque. We then compared the target torque and the measured torque of each task.

Table 1: Questionnaire result [Recognition level of torque].

Evaluation method		Average sco	AEPSD
Valve close	Score	3.860	0.333
	SD	0.180	
Valve open	Score	4.000	0.618
	SD	0.322	
Door knob rotation	Score	3.950	0.557
	SD	0.338	

AEPSD: Average score of each person SD

Tables 1 and 2 show the average, standard deviation (SD), and average score of each subject's SD results from the questionnaire (RLT and ART) for each operation, respectively. These include the variance of the evaluation points. The average RTL result of VC is 3.86, VO is 4.0 and RD is 3.95 respectively. The average ART result of

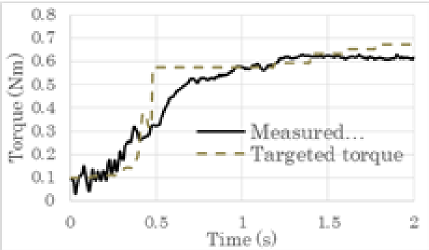
VC is 3.78, VO is 3.82 and RD is 3.88, respectively. The recognition level of torque is 2.8% higher than the authenticity of the represented torque. Standard deviation value of VO is little higher than others.

Table 2: Questionnaire result [Authenticity of the represented torque].

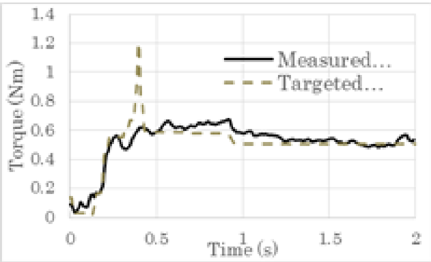
Evaluation method		Average sco	AEPSD
Valve close	Score	3.780	0.276
	SD	0.244	
Valve open	Score	3.820	0.592
	SD	0.289	
Door knob rotation	Score	3.880	0.397
	SD	0.271	

AEPSD: Average score of each person SD

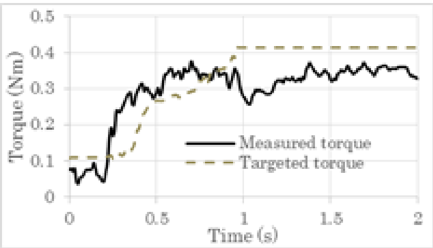
Figure 7 shows examples of the target torque and measured torque. It is difficult to represent rapid torque transitions because the on–off times are set to several dozen milliseconds. Therefore, the maximum torque of the door opening action was difficult to represent to the subject. Overall, the targeted and measured torques had similar shapes.



a) Valve close operation.



b) Valve open operation.



c) Door knob rotation operation.

Figure 7: Examples of target torque and measured torque.

5. Conclusion

We developed a wearable haptic knob display. Torque is generated using a lightweight electromagnetic solenoid braking system and is transmitted to the human wrist flexibly via a string. Our wearable haptic system weighs only 0.4 kg and is easy to wear on the forearm. Our system is an experimental system and we used actual torque for the target torque. We verified the effectiveness of this system by performing three tasks: rotation of a doorknob, closing a valve, and opening a valve. We evaluated it using a five-level questionnaire on the recognition level of the torque and the authenticity of the represented torque. With this experiment, we found that the average force recognition is 3.94 points and the average authenticity of the represented torque is 3.83 on the five-level evaluation. Therefore, the authenticity of the represented torque is a little less effective. For further improvement in the display, we need to improve the realism of rotation tasks. As our system lacks the ability to represent rapid transitions of torques, we used the PWM method for brake control. The typical time of control is several dozen milliseconds for the on–off times. To mitigate this problem, higher friction brake disks or higher power electromagnetic solenoid actuators should be used.

To increase the realism, the rotational axis should be set on a table to provide highly stable rotation. A lightweight display also needs to be constructed, as it difficult to establish a rotational axis for heavy weights for the purpose of wearability.

In this study, we realized a wearable torque generation mechanism in our system. To achieve a perfectly wearable and event-based haptic display, the rotational axis needs to be included in the wearable display, which is a highly challenging task. We also considered the applications of this haptic knob display in evacuation drills, adventure games, and other settings.

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