TorqueBAR: An Ungrounded Haptic Feedback Device

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ABSTRACT
Kinesthetic feedback is a key mechanism by which people perceive object properties during their daily tasks – particularly inertial properties. For example, transporting a glass of water without spilling, or dynamically positioning a handheld tool such as a pen, both require inertial kinesthetic feedback. In this paper, we describe a novel ungrounded haptic feedback device that exploits a kinesthetic awareness of dynamic inertia to simulate complex coupled motion as both a display and input device. As a user tilts our device, called the TorqueBAR, to sense and control computer programmed stimuli, the TorqueBAR's centre-of-mass changes in real-time. We also evaluate the TorqueBAR using both quantitative and qualitative techniques. Finally, we describe possible applications for our device such as video games and real-time robot navigation.

Keywords
Input device, 1 DOF, haptic rod, ungrounded force feedback, two-handed, torque feedback, tilt controller, and mobile computing.

1 INTRODUCTION
Most current devices that provide kinesthetic feedback are grounded (e.g., SensAble's PHANToM [9]); whereas, most ungrounded devices are designed for tactile sensation (e.g., portable Braille displays [12]). Our novel device, the TorqueBAR, contributes to the relatively unexplored domain of ungrounded kinesthetic feedback devices (e.g., Tanaka *et al.*'s Gyro Moment Display [14] and Yano *et al.*'s Gyro effect [17]). Such ungrounded haptic feedback devices can be very useful because they are more mobile and can operate over larger workspaces compared to grounded devices [3].

Our device, called the TorqueBAR, is a coupled input and output prototype intended to explore user interactions with dynamic inertia. The TorqueBAR is a two-handed, ungrounded device with a 1 degree of freedom (DOF) movable centre-of-mass. Figure 1 shows a user interacting with the TorqueBAR. As the user tilts the device, its centre-of-mass shifts in real-time according to a computer-controlled algorithm. A short movie demonstrating a user interacting with the TorqueBAR is available at http://www.cs.ubc.ca/~swindell/torquebar.mp4.

Figure 1: TorqueBAR ungrounded force feedback device

Our motivation for developing and evaluating the TorqueBAR was to explore user performances and preferences of dynamic inertial feedback. We believe that such ungrounded haptic feedback will become increasingly useful in a variety of application areas such as video games and robot navigation. For example, in a race car video game, players often tilt their game controller while navigating a graphical car around sharp turns or obstacles. Some ungrounded video game controllers already incorporate tilt sensing and vibrotactile actuation [5]. A smaller, lightweight version of the TorqueBAR would be a natural extension to such video game controllers, and enhance the gaming experience.

An additional application is real-time robot navigation using teach pendants. During navigation, the robot's end effector or linkages sometimes become visually obscured to the human operator by obstacles in the workplace. A device such as the TorqueBAR could provide spatial information to the operator through visually impaired paths. Subtle haptic cues could also provide warnings of possible collisions with obstacles without overloading the user's visual concentration.

2 APPROACH

The above two application examples illustrate how the TorqueBAR prototype is a first step towards the goal of utilizing dynamic ungrounded kinesthetic feedback in computing applications as much as we do in our everyday actions with ordinary objects such as carrying a glass of water without spilling, or positioning a pen in our hand. We can rapidly prototype many haptic effects with the TorqueBAR and its accompanying testing software. Thus, our system is useful for conducting user studies of dynamic, ungrounded, kinesthetic feedback. We have also designed our system to be incorporated into rapid prototyping strategies such as Wizard-of-Oz design. Future versions of the TorqueBAR could include more degrees of freedom and different form factors such as size and mass.

In this paper, we first summarize and relate the TorqueBAR to related research from psychology and engineering design disciplines. We then describe the implementation of the physical TorqueBAR interface, and its supporting software. Finally we summarize a formal user study that tests performance and user preferences. Specifically, we compare the control of a virtual ball with the TorqueBAR used as a physical input device. Graphic only, haptic only, and graphic + haptic feedback conditions are explored for five different feedback effects.

3 RELATED RESEARCH

Psychology

Turvey [15] has shown that spatial properties of a rod can be accurately perceived by wielding it. People perceive the length of a rod to change with its centre-of-mass even if the overall size and mass of the object does not change. This theory relates to our implementation of the TorqueBAR. By changing the centre-of-mass along the TorqueBAR, Turvey's findings suggest that users will be able to map the TorqueBAR's centre-of-mass to a linear displacement. The results of our user study (described later in this paper) support this theory.

Design

Some devices blur the line between grounded and ungrounded devices. For example, the Rutger Master [2] is a haptic exoskeleton for the hand. Because forces to an individual finger are applied by actuators that are grounded to the user's arm, the device functions similar to a grounded haptic device. It does however have a large workspace and mobility typical of completely ungrounded devices.

Tanaka *et al.* [14] and Yano *et al.* [17] have both developed handheld ungrounded haptic interfaces that do not ground themselves to the user – like the Rutgers Master. Both devices rely on the torque obtained from the gyroscopic effect of a rapidly rotating mass. Tanaka *et al.* [14] use three rotating disks along three Cartesian axes to provide inertial feedback. Yano *et al.* [17] use a single rotating disk with real-time adjustable pitch and yaw to obtain a similar overall force feedback.

Performance comparisons between grounded and ungrounded haptic feedback have been performed by Richard and Cutkosky [11]. They developed and evaluated contact forces using a single servo motor that provided contact resistance to a participant's finger. The same device could provide both grounded and ungrounded feedback over a short spatial range with simple modifications. In general, Richard and Cutkosky found that users of their device performed contact tasks with about double the accuracy with grounded feedback compared to ungrounded feedback. They also found that participants performed contact tasks about 50% more accurately with graphics + haptics feedback compared to haptic only feedback. These results are comparable to those of our study with the TorqueBAR.

The TorqueBAR feedback is similar to the idea of "virtual funnels" described by Wannasuphoprasit *et al.* [16]. By selecting an appropriate virtual model to control the inertial changes in the device, the user may experience the effect known as "virtual funnels". They currently employ this kind of feedback with large grounded robots (called cobots) that can be pushed freely in some directions and resisted in others. By changing its centre-of-mass, the TorqueBAR can spatially funnel user movement.

The concept of extremely lightweight ungrounded haptic feedback has been explored by Kajimoto *et al.* [8]. They use electrical stimulation of nerving in a person's finger tip to simulate the feeling of force feedback. They also include pressure sensors to provide coupled sensing and actuation. Their long term goal is to develop removable tattoos to produce haptic feedback.

Although ungrounded haptic feedback similar to the TorqueBAR has not been implemented into a mobile device such as a Personal Digital Assistant (PDA), all necessary pieces have been explored. For example, Hinckley *et al.*[6] have explored sensing tilt with a mobile PDA and updating graphical feedback accordingly (e.g. scroll text when the PDA is tilted). However, Hinckley *et al.* did not explore active haptic feedback. Noma *et al.*[10] coupled haptic sensing and feedback for a PDA, but their prototype was grounded via a large robot linkage making the device relatively immobile.

4 IMPLEMENTATION

The TorqueBAR system is comprised of a physical interface, input/output controller, and software. The physical interface is a two-handed bar with a moveable centre-of-mass. Both the tilt of the device and the position of the centre-of-mass are measured and updated in real-time (see Figure 2). To demonstrate the use of the TorqueBAR, we also developed a simple video game (see Figure 5).

Physical Interface

Frame and Actuation

The physical interface is a two-handed device with a dynamically controllable centre-of-mass. Before agreeing on the current design, we iterated through rapid prototypes with different dimensions, masses, and handle configurations. After interviewing participants' views of these initial prototypes, we chose the current implementation for the following reasons:

- Two-handled control gave more sensitive feedback to the user because the force exerted on each hand would shift as the centre-of-mass changed (i.e. as the motor moved). Fatigue was also less of an issue with the two-handed device compared to one-handed versions.
- A 200 g motor mass and negligible frame mass would have been good; however, the motor controller that we adapted from Shaver & MacLean [13] was optimized for a motor with a mass of 250 g. Furthermore, we deemed that an ultralight

assembly mass was prohibitively complex and expensive to machine for this initial prototype.

- A 50 cm device length was chosen to be long enough to provide a wide range of force feedback while still enabling adults to comfortably tilt the device ± 45°. The overall width and height were designed to be relatively small, but were not as much of a concern as the overall length.

We built a light-weight frame using square aluminum tubing. Attached to the frame are two steel rods and a Delrin plastic slider. A Pittman 8302S05 DC servo motor is bolted to the slider, and can pull itself along the steel rods using a toothed rubber belt (see Figure 3). The entire slider assembly weighs 350 g, and the entire device weighs 1050 g. To maximize the feeling of a dynamic change in centre-of-mass, we strived to obtain a high mass ratio of *mass-of-slider* : *total-device-mass.*

As shown in Figure 3, the entire interface measures 48 cm long and 11 cm wide. The handles measure 10 cm long with a diameter of 2.5 cm, and are separated by 10 cm.

Sensing

An optical encoder is used to sense the position of the motor, and tilt is sensed with an accelerometer. The encoder included with the Pittman motor has 500 counts / revolution, which corresponds to a linear spatial resolution of 0.13 mm for our pulley-belt system. Tilt is measured using the Analog Device ADXL202AE ± 2 g accelerometer.

I/O Controller

The input/output (I/O) controller is an extension of the Twiddler haptic controller developed by Shaver and MacLean [13]. As illustrated in Figure 4, the Twiddler haptic controller connects a DC servo motor and encoder to a PC via a standard parallel port. Motor control information is received via a pulse width modulated signal that is generated by the Twiddler controller using values from the parallel port's 8 data pins. Positional information is transmitted to the PC from the encoder using the same 8 data pins. Synchronization of the motor and encoder is controlled by the 4 control pins. Twiddler does not use any of the 5 status pins of the parallel port.

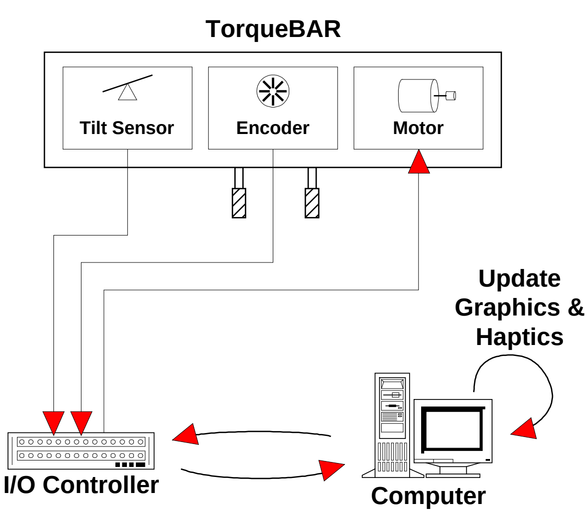

Figure 2: High-level data flow

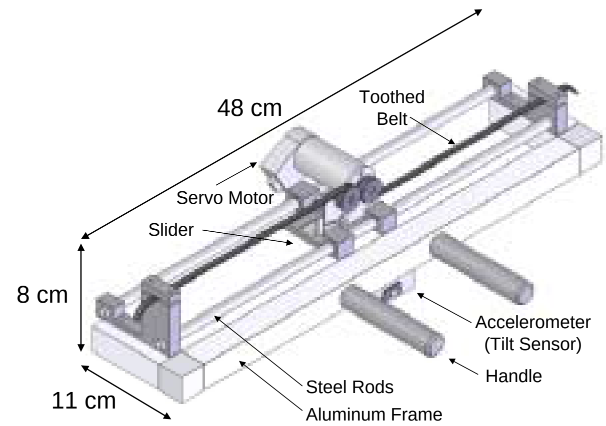

Figure 3: TorqueBAR physical interface

We utilize these 5 previously unused status pins to send tilt information to the PC. As shown in Figure 4, an accelerometer is polled every 2 ms by a PIC microcontroller. An 8 bit tilt angle between ± 45° is send to the PC out the microcontroller's built-in parallel slave port. This angle is accurate within 1° when the device is operated at room temperature (20° C). Because only 5 parallel port pins are unused by Twiddler, we send the 8 bit value in two, 4 bit nibbles. The 5th bit indicates a high or low nibble.

Testing Software

Our testing software has two primary functions:

- Mode 1: Quantitative user performance evaluation
- Mode 2: Qualitative assessment of haptic effects

Because some of our target application areas (such as video games) focus on enhancing the user experience instead of user performance, qualitative assessment is as important, or possibly more important, than quantitative assessment.

Mode 1: Quantitative User Performance Evaluation

Figure 5 illustrates a screen shot of a simple game that we developed to evaluate user performance of the TorqueBAR. The goal of the game is to keep a ball as close as possible within the centre of a semi-circular slide. This ball and slide can be represented graphically on a monitor and/or haptically on the TorqueBAR. Consequently, we test the users' performance under three conditions: graphic feedback, haptic feedback, or graphic + haptic feedback.

The default ball position is in the centre of the slide when the TorqueBAR is held horizontal to the ground. Ball motion is generated from two sources:

- The computer (predefined ball trajectories)
- The user (tilt of the TorqueBAR)

Thus, as the game progresses, the computer program applies simulated forces to the ball, and the user tilts the TorqueBAR in an effort to counteract the ball movement (i.e. keep the ball centred). If the predefined path by the computer moves the ball up the right side of the slide, both the graphical ball and physical motor on the TorqueBAR will move rightward. In this case, tilting the TorqueBAR counterclockwise, would force the ball back towards the centre of the slide.

Mode 2: Qualitative Assessment of Haptic Effects
Qualitative assessments of the haptic performance of the TorqueBAR can also be conducted. For example, an experimenter can move a slider in our graphical user interface while another person holds the TorqueBAR. Interacting with this graphical widget will update the motor position, velocity, and acceleration on the TorqueBAR. Thus, we can rapidly prototype a wide range of haptic effects and Wizard-of-Oz applications.

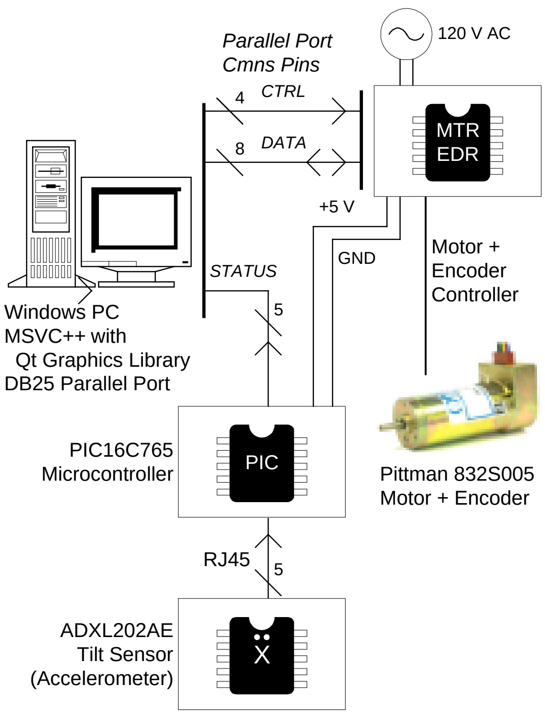

Figure 4: I/O controller components

Design Summary
The software was developed using C++ and the Qt graphics toolkit [1]. Although our software runs on the Windows operating system, it could be ported with relative ease to other operating systems such as Linux.

Figure 6 illustrates the high-level feedback control algorithm for the TorqueBAR. As shown in the Figure, the ball's default

Figure 5: Screen capture of user testing software

setpoint (i.e. linear position) on the TorqueBAR and monitor is specified. Tilting the TorqueBAR in the opposite direction to the ball setpoint will negatively affect the resultant ball position. For example, if the setpoint is to the right of the TorqueBAR's centre; then, tilting the TorqueBAR counterclockwise will move the ball leftward. This resultant position is sent to update the graphical ball on the monitor, and combined with the encoder position to update the physical 'ball' (i.e. motor on the TorqueBAR).

The motor position on the TorqueBAR is updated using a PD (proportional derivative) controller (see Equation 1).

$$F = K_1(x_s - x_m) + K_2(\theta) + B(\dot{x}_m) \tag{1}$$

K_1 = Position spring constant
x_s = Desired position
x_m = Current motor position
K_2 = Tilt spring constant
θ = Tilt angle of TorqueBAR
B = Damping constant
$\dot{x}_m$ = Current motor velocity

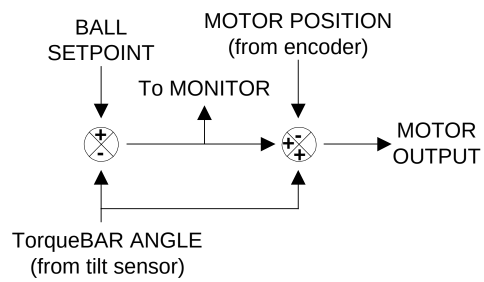

Figure 6: Control flow

5 USER STUDY

Method

Participants
A total of 20 people (16 male and 4 female) participated in this experiment. Participants were ethnically diverse, frequent computer users who ranged in age from 23 to 37 years (M = 27.7, SD = 4.23). Data logs for one additional participant were corrupt; thus, this participant's quantitative data is not reported.

Apparatus
Figure 7 illustrates the experimental setup. Participants stood in front of a 17" computer monitor running the testing software described in §0 on p. 3. Participants were instructed to hold the TorqueBAR with two hands in a comfortable position. All participants' actions were logged into an ASCII text file during the experiment every 3 ms. Participants were instructed to look forward at the monitor. View of participants' hands and the TorqueBAR was obstructed during the experiment. Additionally, sounds from the TorqueBAR mechanism were masked using headphones to a white noise generator.

The graphical slide was 17 cm wide and 8 cm high with a slide radius of 6.5 cm (see Figure 5). The graphical ball was red with a diameter of 1.5 cm. TorqueBAR dimensions are illustrated in Figure 3.

Procedure

The experimenter described the apparatus and procedure to the participant. Three sample trials were then executed to familiarize the participant with the system. One complete trial of the experiment is described in the following paragraph.

Participants were instructed to keep a virtual ball as close as possible to the centre of a virtual slide by tilting the TorqueBAR to oppose the sliding ball. A tilt angle of ± 30° moved the virtual ball to the left or right slide boundary. Participants attempted to oppose one of five pre-computed ball *paths* (sine1, sine2, sine3, square, or square_sine) under one of three feedback conditions (graphics only, haptics only, or graphics + haptics). Table 1 and Figure 8 illustrate each of the 5 paths. Figures 10 and 11 illustrate two example paths (sine2 and square_sine). Participants were instructed to take a rest in between trials as desired (usually 2-3 times per session). During the graphics only condition, the motor was kept directly centred on the TorqueBAR.

Table 1. Virtual ball paths for testing software

Path	Description
Sine1	Sine wave (period of 3 s; amplitude of 21.2°)
Sine2	Sine wave (period of 6 s; amplitude of 21.2°)
Sine3	Sine wave (period of 12 s; amplitude of 21.2°)
Square	Square wave (period of 8 s; alternating amplitudes of +16.5° & -11.8°)
Square_Sine	Square wave away from slide centre (period of 5.2 s; amplitudes of +16.5° & -11.8°) with sine wave return to slide centre (period of 6 s; amplitudes of +16.5° & -11.8°)

Figure 7: Experimental apparatus

At the end of the session, participants were asked to fill out a questionnaire. The first three questions asked to provide rankings on a 7-point scale for each of the feedback conditions. The remaining questions were short answer responses. All the questions are summarized in Table 2.

Table 2: Post-trial questionnaire questions

Scaled responses (for each of three feedback conditions)	
1	I was able to control the player well (preference)
2	I preferred controlling the player (ability)
3	I had fun using the rod device (fun)
Short answer responses	
4	What application(s) do you think this device would be useful for? Why?
5	What application(s) do you think this device would not be useful for? Why?
6	What did you like about this device?
7	What did you not like about this device?
8	Did the device make you feel tired? If so, after how many tests did you start to feel tired?

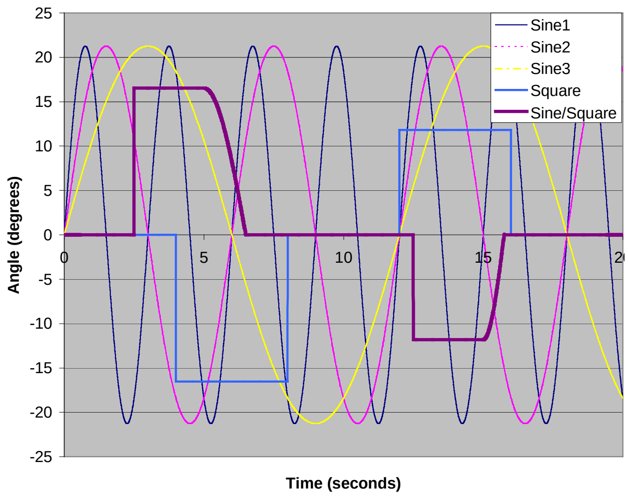

Figure 8: Virtual ball paths for testing software

The experimental design consisted of two within-subject factors (*feedback* and *path*). These two factors were crossed to yield 15 conditions per participant. Two repetitions were conducted to yield 30 trials per participant. The dependent measure was *average ball angle* of the TorqueBAR where *average ball angle* is defined as the average angle the virtual ball in the testing software deviated from the centre of the virtual slide (see Figure 5). Data was randomized to account for possible fatigue or learning effects.

Results

A two-way analysis of variance (ANOVA) showed significant main effects for feedback ($F(1.30, 24.6) = 215.0$ $p < .000$, $\eta^2 = .919$) and path ($F(3.33, 62.3) = 246.7$, $p < .000$, $\eta^2 = .928$). Significant two-way interaction between feedback and path were also observed ($F(5.07, 162.9) = 2.82$, $p = .032$, $\eta^2 = .129$). Huynh-Feldt corrections for sphericity were used for the main effects of feedback (ε = .648) and path (ε = .833), as well as the interaction of feedback and path (ε = .634). Table 3 summarizes the results for the main effect of feedback, and Table 4 summarizes the results for the main effect of path.

Table 3: Average tilt angles for main effect of feedback

Feedback	Graphics Only	Haptics Only	Graphics + Haptics
Mean	5.11°	8.93°	5.12°
SD	2.80°	2.99°	2.46°

Table 4: Average tilt angles for main effect of path

Path	Sine1	Sine2	Sine3	Square	Square/Sine
Mean	10.2°	7.85°	5.40°	3.85°	4.67°
SD	2.57°	2.75°	2.62°	1.76°	1.81°

Least significant difference (LSD) post-hoc analysis of the significant main effects was also conducted. Post-hoc analysis of feedback revealed a significant difference between graphics only and haptics only conditions ($p < .000$), and between graphics + haptics and haptics only conditions ($p < .000$). Post-hoc analysis of path conditions revealed a significant difference between all paths ($p < .003$). Estimated marginal means of feedback and path are shown in Figure 9.

Two example responses under the graphics + haptics condition are shown in Figures 10 and 11. Figure 10 shows an example response to a sinusoidal input (sine2). Figure 11 shows an example path (square/sine) where the testing software generated a step response of the centre-of-mass away from the TorqueBAR centre and a sinusoidal return of the centre-of-mass to the TorqueBAR's centre. The dashed blue line shows the TorqueBAR stimulus, the solid magenta line shows the user response, and the thick yellow line shows the resultant centre-of-mass for the TorqueBAR.

Responses to the first three post-trial questions are summarized in Table 5.

Table 5: Responses to post-trial questionnaire (1 = strongly agree; 7 = strongly disagree)

Question	Graphics Only	Haptics Only	Graphics + Haptics
1 (Mean)	2.0	5.1	2.3
(*SD*)	*1.4*	*1.4*	*1.6*
2 (Mean)	2.2	5.4	2.3
(*SD*)	*1.5*	*1.7*	*1.8*
3 (Mean)	2.7	4.0	2.0
(*SD*)	*1.8*	*2.0*	*1.7*

The relative rankings of for the first three questions are summarized in Table 6.

Table 6: Relative rankings of ability, preference, and fun for all combinations of feedback (G = graphics only; H = haptics only; GH = graphics + haptics)

	G>H	G>GH	G>V	H>GH	GH>G	GH>H
Ability	87%	44%	4.3%	13%	22%	83%
Preference	87%	35%	4.3%	17%	39%	83%
Fun	65%	22%	22%	22%	52%	65%

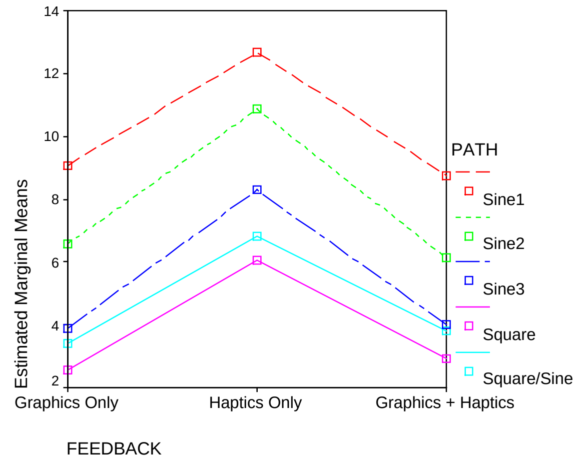

Figure 9: Estimated marginal means of feedback and path

Discussion

Quantitative

Lack of significant difference between the main effects of graphics only and graphics + haptics suggests that the addition of haptic feedback to the graphics only task did not inhibit user performance. However, graphical feedback appears to outperform haptic feedback. In an application such as video games, these results suggest that haptic feedback similar to that provided by the TorqueBAR could be added to a video game controller to enhance the qualitative user experience without affecting the user's game performance. For applications such as real-time robot navigation, these results suggest that visual feedback should be maintained; however, the addition of haptic feedback main prove beneficial in situations where a user needs to temporarily switch their visual attention to another task. In other words, because the haptic only condition accuracy was 75 % worse than graphics only or graphics + haptics conditions, the haptic feedback may be useful during guidance around obstacles where visual feedback of the workspace is temporarily obstructed. However, visual feedback should probably be maintained for motions where high accuracy is needed. These results of participants performing better with graphics + haptics conditions compared to haptics only conditions are consistent with findings by Richard and Cutkosky [11] using their ungrounded haptic feedback device.

As expected, absolute mean results for tilt angle of the three sinusoidal paths (see Table 4) show a decreasing trend in performance as the participants controlled paths of higher spatial frequency. A more interesting result was the significantly better performance when participants recovered from a step response (square wave) compared to a sinusoidal response. This suggests that participants were better able to sense and react to dynamic change (e.g., velocity and acceleration) of the centre-of-mass compared to sensing and reacting to the absolute position of centre-of-mass. Furthermore, this suggests that participants could perform gross discrete movements better than fine continuous movements with a change-of-mass physical interface such as the TorqueBAR. A possibility for this difference is that reaction to the step response is primarily a sub-conscious reaction whereas reaction to the sinusoidal response requires more conscious, less precise attention. This explanation is consistent with two-visual systems psychophysics theory.

Qualitative

We classified the 'like' and 'dislike' participant responses from the questionnaires into 3 and 7 categories, respectively (see Table 7 and Table 8). Participant 'dislike' responses varied greatly compared to the 'like' responses. Almost all participants suggested the TorqueBAR would be most useful for video game applications.

About four times as many participants liked the coupling between haptics and graphics compared participants who disliked the coupling. Of the three participants who did not like this coupling two of them liked the concept of coupling graphics and haptics with the TorqueBAR, but they did not feel the coupling was tight enough. Thus, we observed a strong user preference for the coupling of graphic and haptic modalities with the TorqueBAR.

Participants also found the TorqueBAR fun and engaging to use; however, as expected, extended use might cause be a problem because of the TorqueBAR's mass. We conjecture that a commercial version of a device like the TorqueBAR should have a similar mass to a video game controller (< 200 g). Many participants became fatigued using the TorqueBAR or suggested that the weight would cause them fatigue with extended use. A few participants also suggested that ergonomics could be improved by orienting the handles on an angle out of the TorqueBAR, repositioning them along the length of the TorqueBAR, or by removing the handles all together and creating a smaller device.

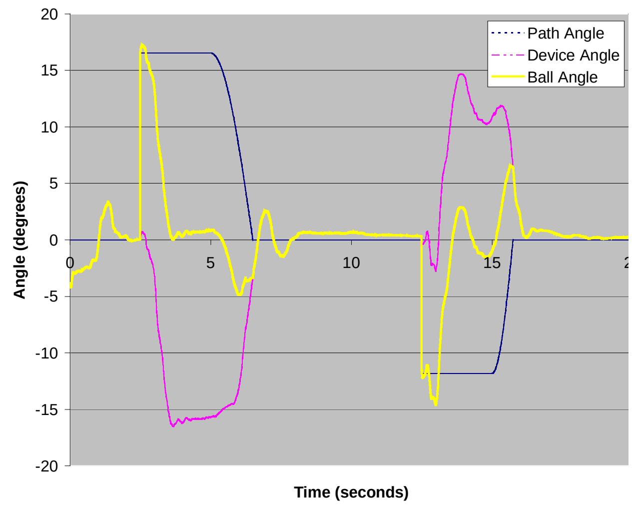

Figure 10: Example path (square/sine)

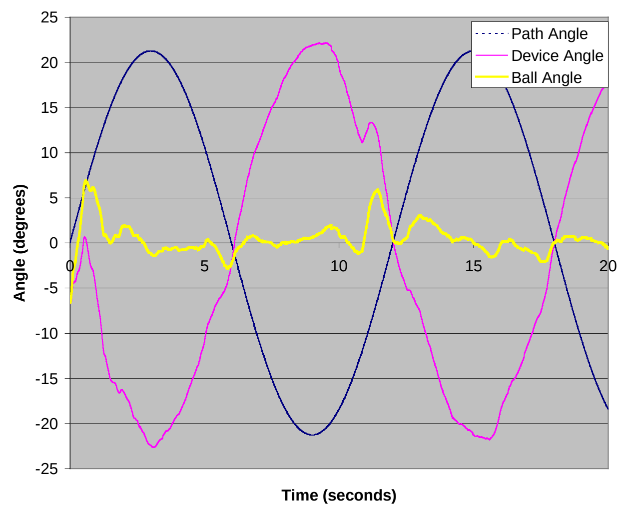

Figure 11: Example path (sine2)

Participants liked the haptic sensitivity afforded by the close proximity of the two handles. Several participants mentioned that they preferred the 'feel' of the haptic feedback at the ends of the TorqueBAR compared to the centre. Specifically, some participants mentioned a 'dead zone' between the two handles. They believed that their haptic sensitivity was reduced when the motor was stationary or slowly moving between the two handles. These comments support our design decision to develop a two-handed haptic feedback device in order to create an effect of a dynamic fulcrum that shifts from hand to hand as the centre-of-mass changes.

Table 7: Participant likes

Category	Number of participants
Haptics + Graphics Coupling	11
Fun	6
Challenging	3

Table 8: Participant dislikes

Category	Number of participants
Weight	8
Haptics Only	6
Fatigue	4
Jumping Ball	3
Haptics + Graphics Coupling	3
Handles	2

6 CONCLUSIONS & FUTURE WORK

We have demonstrated a novel haptic interface that provides ungrounded kinesthetic inertial feedback. Both the quantitative and qualitative user testing with the TorqueBAR suggest that users enjoyed using the TorqueBAR, and they were able to accurately perform complex spatial navigation tasks. The study results also suggest several improvements for future prototypes. A lighter more ergonomic frame combined with smoother, more tightly coupled feedback would enhance the user experience. Such improvements could be easily obtained using a lighter, stronger motor, an encoder with higher resolution, and better systems integration of the accelerometer. Lighter materials such as carbon composites or lightweight plastics could reduce the overall weight.

Although users were able to perform spatial tasks well using the TorqueBAR without any graphical feedback, multimodal feedback (graphics + haptics) was preferred by participants and resulted in significantly better performance.

An unexpected result was the compelling feeling experienced when the motor on the TorqueBAR rapidly accelerated or decelerated. One participant succinctly expressed this rapid acceleration/deceleration feeling along the TorqueBAR as, “Hey! That’s cool man!”. Future device design iterations and user testing could explore this dynamic inertial effect. For example, one participants slightly wielded the TorqueBAR from side to side to feel where the motor was currently located while following a very slow sinusoidal path. Adding higher frequency components to the centre-of-mass may improve user enjoyment and performance of spatial tasks.

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