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 hammer, both require inertial kinesthetic feedback. We describe a prototype for a novel ungrounded haptic feedback device, the TorqueBAR, that exploits a kinesthetic awareness of dynamic inertia to simulate complex coupled motion as both a display and input device. As a user tilts the TorqueBAR to sense and control computer programmed stimuli, the TorqueBAR's centre-of-mass changes in real-time according to the user's actions. We evaluate the TorqueBAR using both quantitative and qualitative techniques, and we describe possible applications for the device such as video games and real-time robot navigation.

Categories and Subject Descriptors
H.5.2 [**INFORMATION INTERFACES AND PRESENTATION (e.g., HCI)**]: User Interfaces – *ergonomics, evaluation/methodology, haptic I/O, input devices and strategies (e.g., mouse, touchscreen), prototyping.*

C.3 [**Special-Purpose and Application-Based Systems**]: Microprocessor/microcomputer applications, Real-time and embedded systems.

General Terms
Design, Human Factors, Measurement, and Performance.

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 physically grounded (e.g., SensAble's PHANToM [9]). Most ungrounded devices are limited to providing merely tactile rather than kinesthetic sensations (e.g., portable Braille displays [12]).

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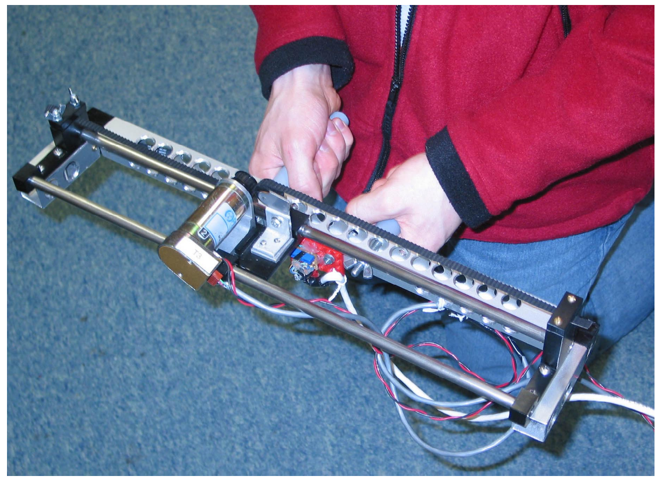

Figure 1: TorqueBAR ungrounded force feedback device

Our device, the TorqueBAR, contributes to the relatively unexplored domain of ungrounded kinesthetic feedback devices (e.g., Tanaka *et al.*'s Gyro Moment Display [15] and Yano *et al.*'s Gyro effect [18]). Ungrounded haptic feedback devices are more mobile and can operate over larger workspaces compared to grounded devices [3].

The TorqueBAR is a coupled input and output prototype intended to explore novel user interactions with dynamic inertia. The TorqueBAR is a two-handed, ungrounded device with a centre-of-mass that moves in 1 degree of freedom (DOF) under computer control. 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. This interaction is illustrated in our accompanying video.

Our motivation for developing and evaluating the TorqueBAR was to explore user performance(s) and preference(s) for dynamic inertial feedback. We believe that 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 controllers while navigating a graphical car around sharp turns or obstacles even when this tilt is not sensed. Some video game controllers already incorporate tilt sensing and vibrotactile actuation [6]. A smaller, lightweight version of the TorqueBAR would be a natural extension to such video game controllers that might enhance the gaming experience.

A second application is real-time robot navigation using a 'teach pendant' (i.e., a handheld physical interface for moving a robot). While controlling a robot's position, the human operator's view of the robot's end effector or linkages is sometimes visually obscured by obstacles in the workplace. A device such as the TorqueBAR could provide this lost spatial information to the operator. Subtle haptic cues could also provide warnings of impending collisions with obstacles without overloading the user's visual concentration.

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.

In this paper, we first review related research from psychology and engineering. We then describe the implementation of the TorqueBAR interface. Finally we describe a 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, exploring graphic, haptic, and graphic+haptic feedback conditions during a controlled simulation.

2. RELATED RESEARCH

Theory from psychology and design from engineering were utilized to develop the TorqueBAR.

2.1 Psychology

Turvey [16] has shown that inertial and kinematic properties of a rod can be perceived by wielding it. People perceive the length of a rod to change with its moment of inertia even if the overall size and mass of the object does not change. We use this idea as the basis for the TorqueBAR. Turvey's findings suggest that moving the centre-of-mass (i.e., moment of inertia) of the TorqueBAR can be perceived as a linear displacement of the centre-of-mass.

2.2 Design

Some devices blur the line between grounded and ungrounded devices. For example, the Rutgers Hand 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 similarly to a grounded haptic device. It does however have a large workspace and mobility typical of completely ungrounded devices.

Tanaka *et al.* [15] and Yano *et al.* [18] have both developed handheld ungrounded haptic interfaces that do not ground themselves to the user as does the Rutgers Hand Master. Both devices rely on the torque obtained from the gyroscopic effect of a rapidly spinning mass. Tanaka *et al.* [15] use three rotating disks along three Cartesian axes to provide inertial feedback. Yano *et al.* [18] use a single rotating disk with real-time adjustable pitch and yaw to obtain a similar overall force feedback. Haptic feedback with the TorqueBAR is different from these devices because the centre-of-mass actually changes in the TorqueBAR.

Performance comparisons between grounded and ungrounded haptic feedback have been conducted 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 using the device performed contact tasks about 50% more accurately with graphic+haptic feedback compared to only haptic feedback.

The mental model for the TorqueBAR's feedback is similar to the idea of "virtual fixtures" defined by Rosenberg [13] as, "abstract sensory information overlaid on top of reflected sensory feedback from a remote environment." By changing its centre-of-mass, the TorqueBAR can likewise spatially guide user movement.

Ungrounded haptic feedback similar to the TorqueBAR has not been incorporated into a mobile device such as a Personal Digital Assistant (PDA); although, some necessary pieces have been explored. For example, Hinckley *et al.*[7] 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.

3. 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 (see Figure 2). Both the tilt of the device and the position of the centre-of-mass are measured and updated in real-time (see Figure 3). To demonstrate the use of the TorqueBAR, we also developed a simple video game (see Figure 5).

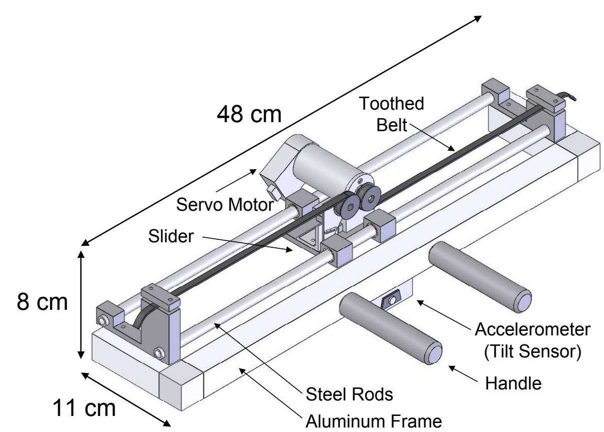

Figure 2: TorqueBAR physical interface. The device's centre-of-mass moves when the motor turns, pulling the motor along the device's rails

3.1 Physical Interface

3.1.1 Frame and Actuation

We prototyped a number of alternative approaches with different dimensions, masses, and handle configurations. After obtaining informal user feedback 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 distribution and direction of reaction force exerted on each hand would shift as the centre-of-mass moved (i.e. as the motor moved). Fatigue was also less of an issue with the two-handed device compared to one-handed versions.

- A length of 48 cm was long enough to provide a wide range of force feedback while still enabling adults to comfortably tilt the device ± 45° with little chance of hitting other objects. The moment of inertia can change substantially by moving the motor along the 24 cm distance to either of end of the TorqueBAR. The overall width and height were relatively small, but less of a concern than the overall length.

Since a typical ungrounded video game controller has a mass less than 200 g, we believed that the best TorqueBAR design would have a very lightweight frame combined with a < 200 g moving mass. We deemed that an ultralight frame was prohibitively complex and expensive to machine for this initial prototype.

We built the 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 2). 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 *moving-mass* : *total-mass*.

As shown in Figure 2, 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.

3.1.2 Sensing

An optical encode 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 toothed-belt system. Tilt is measured using the Analog Device ADXL202AE ± 2 g accelerometer.

3.2 I/O Controller

The input/output (I/O) controller is an extension of the Twiddler haptic controller developed by Shaver and MacLean [14]. As illustrated in Figure 4, the "Twiddler" haptic controller is an electronic device that transmits DC servo motor command output and encoder input to a PC via a standard parallel port, at a 1000 Hz round trip updated rate. 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. The standard Twiddler configuration does not use any of the 5 status pins of the parallel port.

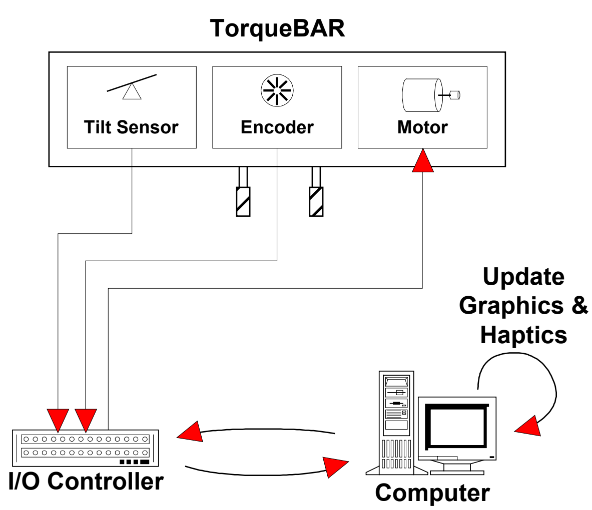

Figure 3: High-level data flow

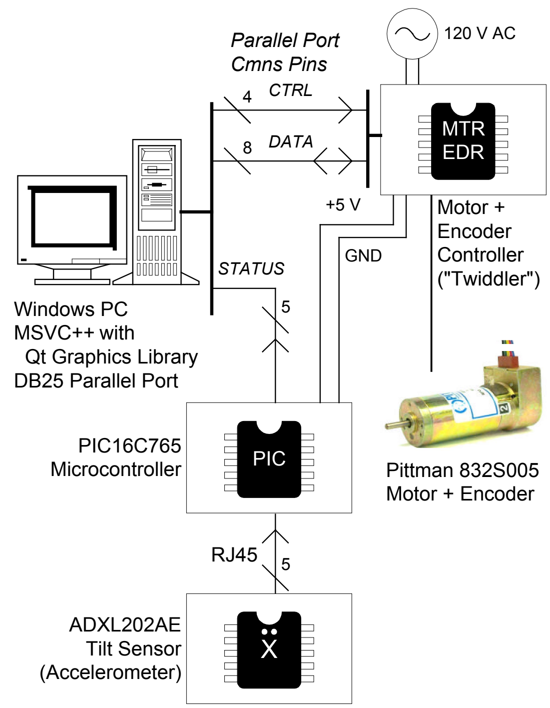

Figure 4: I/O controller components

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. We use a modified algorithm described by Weinberg [17]. An 8 bit tilt angle between ± 30° is sent 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.

3.3 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.

3.3.1 Mode 1: Quantitative User Performance Evaluation

Figure 5 illustrates a screen image 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 to 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.

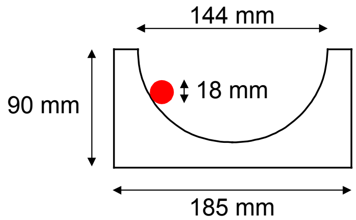

Figure 5: Screen display of user testing software

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 (default ball force 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). The default ball trajectory is a path of a ball rolling down a slide. If the default ball trajectory causes the ball to move 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 increase the force on the virtual ball, drawing it (and the motor) back towards the centre of the slide. We use a direct mapping of the TorqueBAR's tilt to the position of the virtual ball. For example, assuming the computer is not applying any force, if the user tilts the TorqueBAR at an angle α, the virtual ball will move to a position θ_s on the graphical slide, and θ_t on the TorqueBAR (i.e., the motor will move to position θ_t).

3.3.2 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 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.

3.3.3 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 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 by increasing the resultant force on it. This resultant position is sent to update the graphical ball on the monitor, and subtracted from the encoder position to create an error signal used 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).

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

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

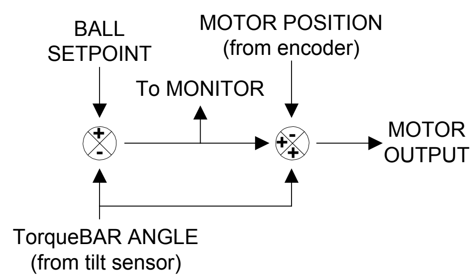

Figure 6: Control flow

4. USER STUDY

4.1 Method

4.1.1 Participants

A total of 20 people (16 male and 4 female) participated in this experiment. Participants were right-handed, 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.

4.1.2 Apparatus

Figure 7 illustrates the experimental setup. Participants stood in front of a 17″ computer monitor running the testing software described in §3.3 on p. 3. Participants were instructed to hold the TorqueBAR with two hands in a comfortable position. Participants' actions were logged into an ASCII text file during the experiment every 3 ms. Participants were instructed to look forward at the monitor, and not at their hands (or the TorqueBAR) during the experiment. We obscured their view of their hands with a black plastic barrier to so their visual feedback of the TorqueBAR was obtained exclusively from the monitor. We additionally shielded participants from audio feedback of the TorqueBAR's movement to ensure that all feedback was graphic and haptic. Sounds from the TorqueBAR mechanism were masked using headphones attached to a white noise generator.

The graphical slide dimensions are illustrated in Figure 5. Physically tilting the TorqueBAR ± 30° will cause the motor (virtual haptic ball) to slide to the end of the device, and/or the graphical ball to slide completely up the side of the graphical slide. Note that these device reaction descriptions assume that only the user input is used to update the virtual ball position (i.e., there is no conflicting virtual model from the computer).

4.1.3 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° was necessary to move the virtual ball all the way 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 (graphic, haptic, or graphic+haptic). Table 1 and Figure 8 illustrate each of the 5 paths. Figure 10 and Figure 11 show data for two example paths (sine2 and square/sine). Participants were instructed to rest between trials as desired (usually 2-3 times per session). During the graphic condition, the motor was kept directly centred on the TorqueBAR at all times, so that it always felt the same.

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°)

At the end of the session, participants were asked to fill out a questionnaire. The first three questions requested 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?

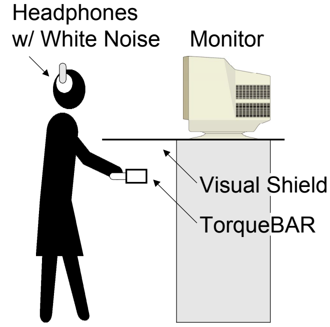

Figure 7: Experimental apparatus

The experimental design was based on two within-subject factors (*feedback* and *path*). The *feedback* factor had 3 levels (graphic, haptic, and graphic+haptic), and the *path* factor had 5 levels (sine1, sine2, sine3, square, and sine/square) as shown in Figure 8. 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, defined as the average angle the virtual ball in the testing software deviated from the centre of the virtual slide (see Figure 5). A perfect score would have resulted from the virtual ball remaining exactly in the centre of the TorqueBAR during the entire trial. Trial order was randomized to account for possible fatigue or learning effects.

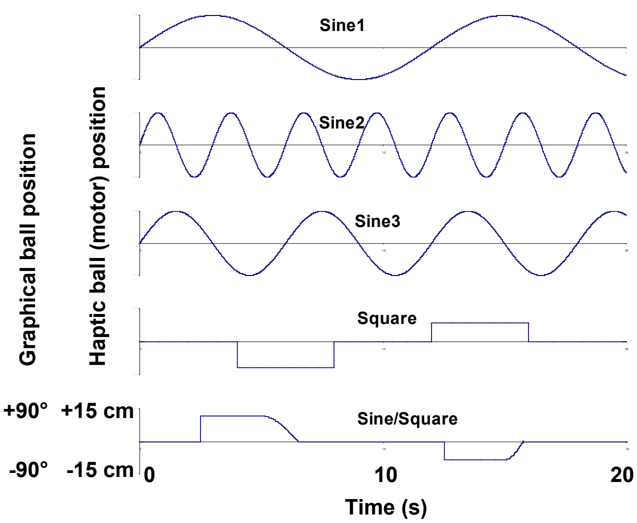

Figure 8: Virtual ball paths for testing software (before user interaction)

4.2 Results

A two-way analysis of variance (ANOVA) showed significant main effects for feedback ($F(1.30, 24.6) = 215.0$ $p < .001$, $\eta^2 = .919$) and path ($F(3.33, 62.3) = 246.7$, $p < .001$, $\eta^2 = .928$). 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 ($\in = .648$) and path ($\in = .833$), as well as the interaction of feedback and path ($\in = .634$). 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	Graphic	Haptic	Graphic+Haptic
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 graphic and haptic conditions ($p < .001$), and between graphic+haptic and haptic conditions ($p < .001$). Post-hoc analysis of path conditions revealed a significant difference between all paths ($p < .003$). Figure 9 shows estimated marginal means of feedback and path.

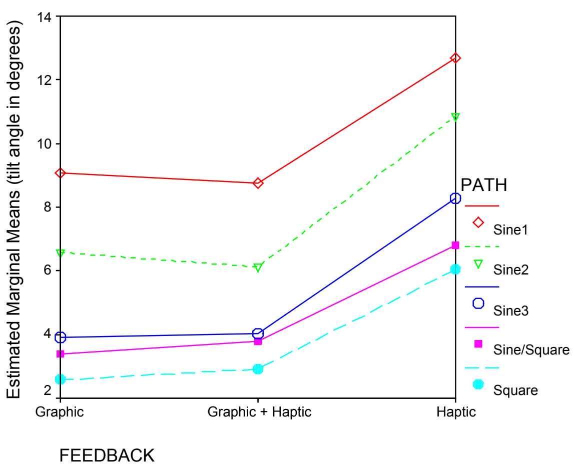

Figure 9: Estimated marginal means of feedback and path

Two example responses under the graphic+haptic 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 grey textured line shows the TorqueBAR stimulus (i.e., Path Angle), the thick black line shows the user response (i.e., Device Angle), and the thin red line (i.e, Ball Angle) shows the resultant centre-of-mass for the TorqueBAR.

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

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

Question	Graphic	Haptic	Graphic+Haptic
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 = graphic; H = haptic; GH = graphic+haptic)

	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%

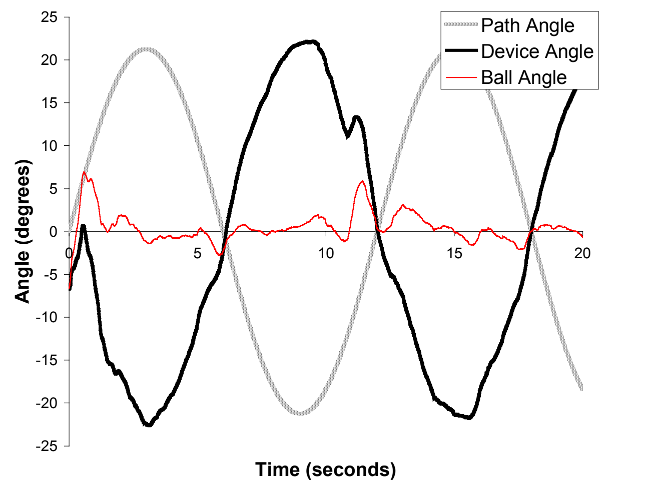

Figure 10: Example path (sine2)

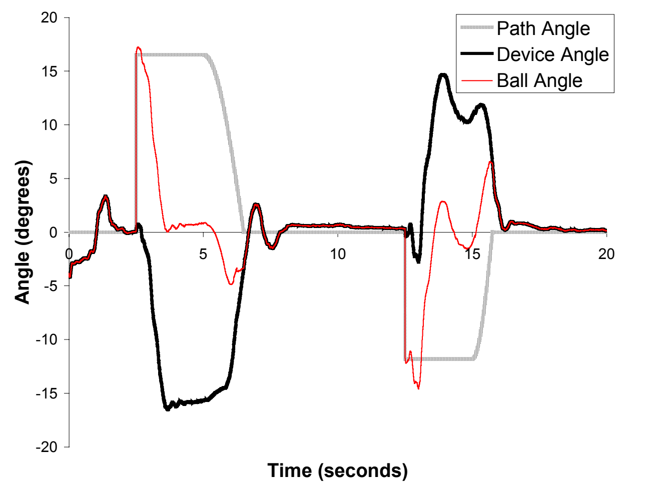

Figure 11: Example path (square/sine)

4.3 Discussion

4.3.1 Quantitative

Lack of significant difference between the main effects of graphic and graphic+haptic suggests that the addition of haptic feedback to the graphic task did not inhibit user performance. However, we were disappointed by the result that graphic feedback outperformed 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 may prove beneficial in situations where a user needs to temporarily switch their visual attention to another task. In other words, if we did not have graphic feedback, the haptic feedback performance (i.e., ~75% worse than graphic or graphic+haptic feedback) may be tolerable for low precision applications. However, visual feedback should probably be maintained for motions where high accuracy is needed. These results of participants performing better with graphic+haptic conditions compared to haptic conditions only 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 path frequency. All the path frequencies were chosen to be well below the TorqueBAR slider's frequency response (Note: When responding to an impulse input, the TorqueBAR slider could instantaneously respond at a velocity of 0.1 m/s and reach a steady-state velocity of 0.3 m/s.). 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.

4.3.2 Qualitative

We classified the 'like' and 'dislike' participant responses from the questionnaires into 3 and 7 categories, respectively (see Table 7 and Table 8). These responses were collected from the short-answer freeform questions on the post-trial questionnaire. Participant 'dislike' responses varied greatly as 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 presence of haptics and graphics together to participants who disliked this coupling of haptic+graphic feedback. 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, subjects commented that extended use might be a problem because of the TorqueBAR's weight. 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.

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.

This 'dead-zone' could be useful in situations such as robot navigation where a device like the TorqueBAR provides spatial warnings. For example, when navigating along a path without any major obstacles, the motor would reside in the 'dead-zone'. Consequently, the haptic feedback would be small and would not compete for the user's attention.

Table 7: Participant likes

Category	Number of participants
Haptic + Graphic Presence	11
Fun	6
Challenging	3

Table 8: Participant dislikes

Category	Number of participants
Weight	8
Haptic	6
Fatigue	4
Jumping Ball	3
Haptic + Graphic Presence	3
Handles	2

5. 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.

Future versions of the TorqueBAR could also include more degrees of freedom and/or different form factors. Higher degrees of freedom would allow changing the moment of inertia in a plane or volume. Aside from ergonomic considerations, different form factors could significantly affect the response characteristics of the physical interface because different actuators could be used with some form factors but not others. For example, using a smaller, lighter motor, and/or different belt configurations, we could easily obtain faster velocities and accelerations.

The effects of lag could be tested by artificially introducing lag into the TorqueBAR, and measuring the effect on user performance. Using the results from a user study conducted under different lag conditions, we could then attempt to extrapolate lag specifications that would correspond to a desired level of user performance with the TorqueBAR.

Although users were able to perform spatial tasks well using the TorqueBAR without any graphical feedback, multimodal feedback (graphic+haptic) was preferred by participants and resulted in significantly better performance compared to haptic feedback. Performance and preference results with graphic feedback and graphic+haptic feedback were almost the same.

An unexpected result was the compelling feeling experienced when the motor on the TorqueBAR rapidly accelerated or decelerated. One participant even said, "Hey! That's cool man!". Campbell *et al.* [4] found that navigating boundaries with discrete textured ridges yielded significantly fewer errors, but longer completion times, compared to navigating paths with gradient textures. These observations suggest that future device design iterations could explore the addition of high frequency vibrations carried on a low frequency waveform (e.g., similar low frequency trajectories to those in the user study described above.) From our informal tests and work such as Campbell *et al.* [4], we believe that greater sensitivity may result from the addition of 'sharper' force cues. Additional informal tests suggested that the moving mass on the TorqueBAR felt heavier if we increased the velocity of the motor response near the centre of the TorqueBAR while keeping the velocity response at the ends of the TorqueBAR constant. These ideas of dynamically changing the haptic response characteristics are examples of the more general idea of adding feedback where a physical, real-world equivalent haptic effect is difficult or impossible to achieve.

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