Relationships Between Human and Automated System Identification of Physical Controls

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Abstract

Active haptic renderings need not only mimic the physical characteristics of a mechanical control such as a knob or slider. They must also elicit a comparable subjective experience from a human who uses the physical control. We compare the results of automated and human captures of 4 salient static and dynamic physical parameters for 5 mechanical test knobs. The automated captures were accomplished using our custom rotary Haptic Camera tool. Human captures were accomplished through user studies in which users matched active haptic renderings to passive mechanical test knobs by adjusting the parameters of the model for the active knob. Both quantitative and qualitative results from the experiments support the hypothesis that the renderings evoke a subjective experience similar to the mechanical knob.

1 Introduction

A key assumption underlying the work reported in this paper is that active haptic rendering can mimic not only the physical characteristics of a mechanical control but also elicit a comparable subjective experience from a human who uses the physical control. We describe a particular rendering system (hardware and algorithm) that uses these models, and tests the hypothesis that the rendering system accurately conveys to the user the "feel" of a physical control given its model. This is accomplished through a user study in which users matched an active haptic rendering to a passive mechanical test knob by adjusting the parameters of the model for the active knob. Both quantitative and qualitative results from the experiment support the hypothesis that the renderings evoke a subjective experience similar to the mechanical knob.

We first describe the rendering system, then we describe the user study and interpret the results of the study in terms of the stated hypothesis. We then discuss how the user study might be improved, and how the choice of parameters in the rendering model might have influenced the results of the study. We close with some general design guidelines based on our results.

2 Related Work

We base our work on both physical characteristics of mechanical controls and the human experience of these mechanical controls. Position-, velocity-, and acceleration-based physical characteristics correspond to effects such as detents, damping, and inertia, respectively. Although these mechanical properties have been developed and used for centuries, current research focuses on active renderings of these properties and systematic study of humans experiencing these properties. For

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example, Colgate and Schenkel [1] suggested a 'virtual mass' method for stably rendering inertia. And, MacLean and Enriquez [10] studied the perceptual salience of detents rendered on a haptic knob using different waveform types, amplitudes, and frequencies.

We first summarize research related to physical characterization of mechanical controls. Richard et al. [16] characterized the friction properties of three surfaces by linearly sliding across each surface with a load cell. The velocity and acceleration parameters were fitted using a least-squares algorithm. MacLean [9] used a haptic interface to measure the non-linear stiffness of a momentary switch using a piecewise linear model. Different regions of the switch were individually characterized using non-linear force versus position curves. Miller and Colgate [11] also characterized force versus displacement data. They used a wavelet network to work in the spatial frequency domain, thus avoiding the need to manually segment out different linear and non-linear regions. Weir et al. [27] took a very pragmatic approach by visualizing mechanical properties of switches using colored plots of position, velocity, or torques. Differences between switches were compared by looking at the same 2D or 3D "haptic profiles". However, these "haptic profiles" were not modelled (parameterized). Modelling and parameterization provides us with a mechanism to analyze, modify and flexibly render the captured dynamics.

Our work also builds upon human factors research involving passive mechanical controls. For example, Woodruff and Helson [28] studied human sensitivity to knob turning tasks involving various torques. Also, Knowles and Sheridan [6] studied participant sensitivities and preferences between knobs with different levels of friction and inertia. Such groundwork research has since been collected into general human factors design books such as Woodson et al. [29]. More recent user studies have targeted active haptic renderings. For example, Lederman et al. [8] tested participants' active and passive sensitivities to different surface textures at different exploration velocities.

Once we know *what* human physical sensitivities exist, modelling research helps define *how* and *why* these human psychophysics work. For example, Novak [13] defined a non-linear mass-spring model to represent typical human wrist motion. It is applicable for describing complicated finger and wrist turning motions associated with knob turning tasks.

Our research presented in this paper is a *synthesis* contribution combining knowledge of what is technologically feasible with what is physiologically significant. An example previous synthesis contribution is Rogers et al.'s [17] comparison of the appropriateness of different input devices for graphical user interface performance tasks. Also, Norman [12] discusses the emotional reactions people have to products – including the physical controls of products. We focus on purely haptic effects of physical controls, but interactions with other modalities, such as vision and audio, can strongly influence the overall user experience and perception of the same haptic effects [21]. Kalid and Helander [5] provide an example multi-modal framework for assessing appropriate design needs within consumer products.

Contemporary haptics research is at a stage of appropriate model building that parallels early vision work in red-green-blue (RGB) tri-chromatic color spaces (see [19] & [30]). Most color televisions and computer monitors blend combinations of red, green, and blue to produce a seemingly full spectrum of colors for a human observer. For example, colors such as yellow and magenta can be effectively

conveyed by blending combinations of primary RGB colors. Color displays would be prohibitively complex and expensive if they needed to instead display individual colors using an array of individual wavelengths for individual colors. Thus, user studies exploring the appropriate color models, such as tri-chromatic color spaces, for human observers were crucial initial research steps for successful, widespread adoption of color displays within our work and leisure environments. We need to figure out the most perceptually important haptic attributes to develop more useful active haptic renderings. What are haptic efficiency equivalents of graphic RGB color spaces?

3 Experiments

Position, velocity, and acceleration parameters of physical controls were estimated using automated and human system identification procedures.

Knobs were chosen as test physical controls, but we conjecture that our analyses are generalizable to other mechanical and rendered physical controls such as sliders and buttons. Five mechanical knobs listed in Table 1 were chosen in a way representing a wide range of position-, velocity-, and acceleration-dependent effects. We conjectured that the subtle friction and detent properties of knob 4 would be particularly difficult for humans; and, the non-linearities of knob 5 would pose difficulty for our automated procedure because knob 5's dynamics clearly violate the procedure's underlying mathematical model.

Table 1: Intuitive descriptions of test knobs

#	***Description***
$Knob_{high\ friction}$	Uniform position; moderate friction; low inertia
$Knob_{high\ inertia}$	Uniform position; low friction; high inertia
$Knob_{subtle\ detents}$	Very subtle, consistent detents of 30 'clicks' / 360°; low friction; low inertia
$Knob_{moderate\ detents}$	Moderate, consistent detents of 12 'clicks' / 360°; moderate friction; low inertia
$Knob_{non\text{-}sine\ detents}$	Wide, non-sinusoidal detents with backlash of 12 'clicks' / 360°; moderate friction; low inertia; non-linearities known to be inconsistent with the fitting model used by the automated system – very difficult to fit

3.1 Automated System Identification

The automated system identification procedure, and data for the test knobs in Table 1 are presented below. These data are then analyzed together with their respective data collected from human participants in §4. Apparatus construction and capturing are described in greater detail in previous research by Swindells & MacLean [23] & [24].

3.1.1 Apparatus

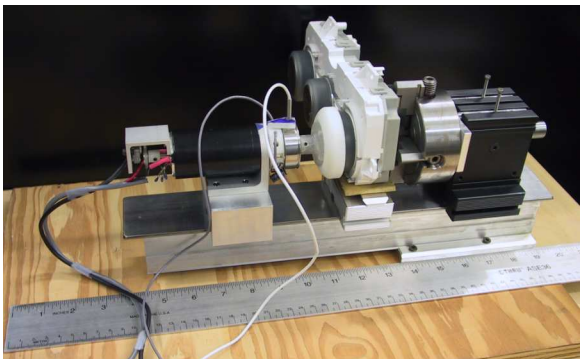

Figure 1: Automated system identification apparatus

The apparatus shown in Figure 1 was used to capture and fit data to Equation 1. Table 2 summarizes captured spatial and torque resolutions using the system identification apparatus. Position values were obtained with a MicroE M2000-M05-256-4-R1910-HA encoder; velocity values were obtained by differentiating the position values; and, acceleration was obtained using an Analog Devices ADXL 202 micromachined accelerometer mounted in a custom ABS (Acrylonitrile Butadiene Styrene) housing. Torques were measured with a Honeywell-Sensotec QWFK-8M rotary torque sensor amplified with a custom Analog Devices AD524CD based instrumentation amplifier. Rotary actuation was performed with a ±12 V Maxon RE40 DC motor providing 180 mNm continuous torque, and a Copley 2122 PWM (Pulse Width Modulation) amplifier providing 10 A continuous current.

Table 2: Capture sensor resolutions

Position (rad)	***Velocity (rad/s)***	***Acceleration (rad/s^2)***	***Torque (Nm)***
9.8 x 10^{-6}	2.0 x 10^{-4}	2.8	1.8 x 10^{-4}

$$\tau = \begin{array}{c} M_{acc}\ddot{\theta} + \\ C_{vel-}\operatorname{sgn}\dot{\theta}_{-} + B_{vel-}\dot{\theta}_{-} + C_{vel+}\operatorname{sgn}\dot{\theta}_{+} + B_{vel+}\dot{\theta}_{+} + \\ A_{pos}\sin\left(\theta / P_{pos} + S_{pos}\right) \end{array} \quad (1)$$

τ	Torque applied to the haptic actuator [Nm]
$\theta, \dot{\theta}, \ddot{\theta}$	User's hand position, velocity, and acceleration applied to the actuator [rad, rad/s, rad/s^2]
M_{acc}	Acceleration value intuitively similar to inertia [Nm / rad/s^2]
C_{vel-}, C_{vel+}	Negative & positive values of dynamic friction [Nm / rad/s]
B_{vel-}, B_{vel+}	Negative & positive values of viscous friction [Nm / rad/s^2]
$A_{pos}, P_{pos}, S_{pos}$	Position parameters for amplitude, period, and phase shifts, to render detents. [Nm, 1, rad]

A 5000 Hz update rate with < 20 µs consistency was obtained using a 3.0 GHz PC with 2 GB of RAM running a Timesys 4.0 Linux kernel. The sensors and actuators were interfaced to the PC via a Measurement Computing DAS1602 I/O board. Software development was written in C++ using custom ACE/TAO based middleware — real-time platform middleware (RTPM) (See Pava and MacLean [15]).

3.1.2 Procedure

Two independent automated sets of captured spatial and torque data for each test knob in Table 1 were fit to Equation 1. Matlab's "lsqcurvefit" and "\" commands were used to fit the non-linear and linear model parts, respectively. A completely non-linear approach was not taken because linear fitting techniques typically converge faster and more reliably than non-linear techniques, and do not require initialization. Non-linear function minimization was forced to use the Levenberg-Marquardt method instead of the more traditional Gauss-Newton method because the Levenberg-Marquardt method has been shown to perform a better fit when using

medium-scale problems such as the ones for the test knobs [1].

3.1.3 Results

Human identification pilot studies with four mechatronic experts suggested that participants experienced too much cognitive load while adjusting five or more knob parameters at once. Consequently, the full capture model of Equation 1 was simplified to four parameters M_{acc}, B_{vel}, A_{Pos}, and P_{pos}. Recent short-term memory researchers have observed that people have a single central memory capacity limit averaging about 4 chunks of information [2].

Parameter reduction was accomplished by simplifying the friction and detent model components. C_{vel+} & B_{vel+} were assumed to be roughly symmetrical to C_{vel-} & B_{vel-}, respectively. Because the human participants were asked to focus on rotary motion, we use a damping parameter, B_{vel}, that focuses on viscous frictional components. Detent phase shift inconsistencies, S_{pos}, between system and human identifications are simply ignored with negligible effect on the more prominent amplitude and frequency components. In other words, we focus on higher quality automated system-to-human comparisons of the four influential position-, velocity-, and acceleration- parameters instead of lower quality comparisons of a larger number of parameters. Mean values from the automated captures are presented in Table 3.

Table 3: Automated measured parameters

	Knob				
	High friction	***High inertia***	***Subtle detents***	***Moderate detents***	***Non-sine detents***
M_{acc}	.081	.28	.035	.049	.0018
B_{vel}	49	9.0	2.3	1.1	24
A_{pos}	-	-	1.1	-11	-130
P_{pos}	-	-	.22	.48	.41
95% CI	.31	.19	.091	.072	4.2

3.2 Human System Identification

The human system identification method, and data for the test knobs in Table 1, are presented below. These data are then analyzed together with their respective data collected from the automated procedure in §4.

3.2.1 Participants

We recruited both novice and expert participants. Novices were chosen because they represent a typical user's sensitivity and vernacular understanding of how detents, friction, and inertia feel. Experts (individuals with training in mechanical systems and models) were chosen to explore the bounds of human perception of mechanical control dynamics. Experts had a heightened awareness of how underlying physics and mathematics change the feeling of detents, friction, and inertia, as well as language to verbalize these percepts. For example, experts understand the differences between Karnopp and Stribeck friction models, understand that detents can be modeled with torque versus position sinusoids, and that inertia is a predominantly acceleration-dependent effect. Novices relied solely on their daily experiences with physical controls such as knobs, whereas experts also relied on their thorough understanding of mechanics.

The procedures for the novice and expert user studies differed slightly in an effort to better utilize their respective skill sets. Generally, experts were given more freedom and more background information than the

novices in an effort to focus on more subtle and refined dynamic attributes of the physical controls.

Right-handed, paid participants were individually tested in the two parts (novice and expert) study. Both parts took approximately one hour to complete. Fifteen novices (10 female & 5 male) with ages ranging from 20-29 years (M = 24.7, SD = 2.8), and five experts (3 male & 2 female) with ages ranging from 23-31 years (M = 27.2, SD = 3.2) participated. Novices were students or staff at the University of British Columbia. Experts were graduate students or post-doctoral students from Mechanical Engineering laboratories at the University of British Columbia employed in haptic-related research projects. None of the experts were directly affiliated with, or knowledgeable of, the authors' research.

3.2.2 Apparatus

Participants interacted with the apparatus shown in Figure 2. By adjusting four physical sliders, participants changed the dynamics of a haptic knob to match the dynamics of five 'real' mechanical test knobs (one at a time) to the best of their ability. These five test knobs were labeled sequentially with letters "A" - "E". The four physical sliders controlled magnitudes of the four rendering parameters M_{acc}, B_{vel}, A_{Pos}, and P_{pos} in Equation 2 (refer to Equation 1 for variable descriptions), as applied to the current virtual knob rendering. Table 4 lists the minimum (bottom) and maximum (top) slider settings.

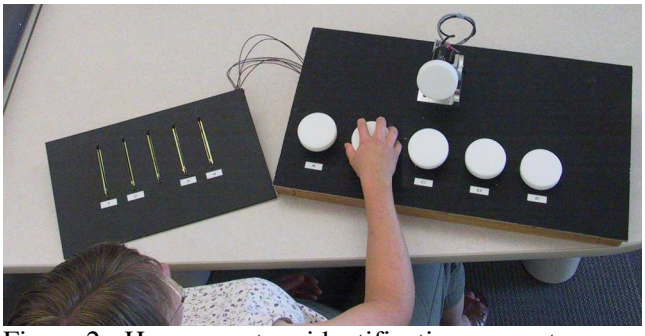

Figure 2: Human system identification apparatus

$$\tau = M_{acc}\ddot{\theta} + B_{vel}\dot{\theta} + A_{pos}\sin\left(\theta / P_{pos}\right) \qquad (2)$$

Table 4: Slider value ranges

Slider	*Minimum → Maximum Values*
M_{acc}	0 → .75 mNm / rad/s2
B_{vel}	0 → 30 mNm / rad/s
A_{Pos}	0 → 15 mNm
P_{pos}	∞ → 5 (0 → 32 detents / revolution)

At the right side of Figure 2, a custom built haptic knob can be seen centred above the 5 equally spaced mechanical test knobs listed in Table 1. The haptic knob and 5 mechanical knobs were all fit with custom ABS caps with a 70 mm diameter, 16.5 mm depth, and 3 mm fillet. These knob caps all had uniform white color and surface texture to ensure participant results focused on mechanical dynamics instead of visual or static haptic properties. Additionally, subjects wore noise cancelling headphones during experimental trials to minimize audio influences. Typical embedded force-feedback knobs have update rates < 1000 Hz, < 2500 CPR (counts per revolution), and < 30 mNm continuous torque [18]. For improved data quality, the same DC motor and position sensor used for the automated system identification apparatus were used to build a custom haptic knob with a 10 000 Hz update rate, 640 000 CPR, and 180 mNm continuous torque. To prevent tethering the haptic knob, inertia was rendered using the virtual mass method suggested by Colgate & Schenkel [1] instead of direct measurement using an accelerometer.

As illustrated in Figure 39, the sliders were visually chunked into a pair of physical sliders for modifying M_{acc} and B_{vel}, separated by an empty slot, and a pair of physical

sliders for modifying A_{pos} and P_{pos}. The sliders for M_{acc} and B_{vel} independently adjusted the respective feelings of inertia and friction, whereas A_{pos} and P_{pos} worked together to adjust the detents (refer to Equation 2). The mechanical test knobs were organized according to this "division by detents". $\text{Knob}_{\text{high friction}}$ (labeled "A") and $\text{Knob}_{\text{high inertia}}$ (labeled "B") did not have detents, whereas knobs $\text{Knob}_{\text{subtle detents}}$, $\text{Knob}_{\text{moderate detents}}$, and $\text{Knob}_{\text{non-sine detents}}$ had detents (labeled "C", "D", and "E"). Sliders A_{pos} and P_{pos} were therefore not needed to model $\text{Knob}_{\text{high friction}}$ and $\text{Knob}_{\text{high inertia}}$.

For the qualitative aspect of the study, participants were also given sticky notes and a pen. They were then asked to label the sliders with descriptive keywords.

The five test knobs (refer to Table 1) that were automatically captured using the Haptic Camera apparatus were each provided with matching smooth, white ABS plastic caps. The test knobs were organized along a row beneath the haptic knob, which was also provided with a similar plastic cap. Each plastic cap measured a 70 mm diameter, 16.5 mm depth, and 3 mm filleted edge. These caps ensured participants compared only the dynamic properties of the knobs, not textural surface properties on the handle. Exposing participants to the surface textures of the test knobs would have introduced additional haptic noise, and visual multimodal effects, into the comparisons.

Disguising the identity of the active haptic knob from the participants would eliminate chances of participants being influenced by their preconceived biases towards either an active knob or a passive test knob. A randomized layout designed to disguise the identity of the haptic knob was not used because the rendered knob would quickly become apparent to the participant with any such layout. Participants would readily determine a controlled active knob within a set of test knobs because an active knob would change its dynamics as the participants adjusted physical slider settings. But, the test knobs would not change.

3.2.3 Procedure

The experimenter manually reset the physical sliders to their off (bottom) positions at the beginning of each session and individual trial. In a familiarization phase, participants were instructed to explore the effects of each slider on the haptic knob. They were first instructed to alter M_{acc}, then B_{vel}. Next they were instructed to move A_{pos} and P_{pos} near the middle of each slider's range, and observe the effects of each position-based slider. Participants explored the effects of each slider on the haptic knob until they felt comfortable and confident using the apparatus. They then wrote down keywords on sticky notes to describe each slider's effect on the haptic knob. Each of these sticky notes were affixed beneath the appropriate physical slider. During this apparatus exploration phase, the experimenter aurally described the underlying physics (mass, damping, detent amplitude, and detent frequency) modified by each slider to the expert participants, but not to the novices. The experts would likely be able to determine the underlying physics themselves; so, explicitly telling the experts these underlying physics allowed us to more quickly progress towards studying more interesting, subtle knob attributes.

In an effort to minimize participant bias, none of the participants were told whether the five test knobs were mechanical or mechatronic (force-feedback) knobs; nor were specific inertia, friction, or detent properties of the five test knobs discussed with any of the participants.

For the novice participants, the knobs were tested in two groups: (i) without detents, and then (ii) with detents. The order of knobs

was randomized within each group and only the relevant sliders were made accessible for each group (M_{acc} and B_{vel} for knobs without detents, and M_{acc}, B_{vel}, A_{pos} and P_{pos} for knobs with detents). This ordering of studying knobs without detents before knobs with detents was justified due to the benefits in learning accrued from gradually increasing the task's cognitive load. Novices were instructed to take as long as they desired (typically about two minutes) to adjust the M_{acc} and B_{vel} sliders to match each knob a total of three times. First, participants were required to match either $\text{Knob}_{\text{high friction}}$ then $\text{Knob}_{\text{high inertia}}$, or vice-versa (knobs without detents). After performing three repetitions with each of the two knobs without detents ($\text{Knob}_{\text{high friction}}$ and $\text{Knob}_{\text{high inertia}}$), they were then instructed to adjust all four sliders to match three repetitions with each of the knobs with detents ($\text{Knob}_{\text{subtle detents}}$, $\text{Knob}_{\text{moderate detents}}$, and $\text{Knob}_{\text{non-sine detents}}$).

For each repetition, a randomized ordering of the knobs was presented to the participant. A trial consisted of using physical sliders to match the "feel" of the active knob to match the "feel" of a test knob as closely as possible, then rate how similar these two knobs felt. For all trials, participants were instructed to rotate the knobs with their right (dominant) hand, and adjust the sliders with their left (non-dominant) hand. This protocol prevented additional noise in the collected data caused by perceptual and/or cognitive differences related to right and left hand usage. After each trial, participants were asked to rate how satisfied they were with the match between the rendered haptic knob and the mechanical test knob. Participants gave a rating between 1 for strongly agree and 9 for strongly disagree to the question, "I am satisfied with the match between the rendered and mechanical knob."

Experts followed the same procedure as the novices, except the experts were instructed to (i) adjust all four sliders when matching all five test knobs, and (ii) perform one very careful block consisting of a randomized ordering of the five test knob trials, in lieu of three rapid, repeated trials. Adjusting all four sliders for all five test knobs was not believed to be a burden because the experts were trained in mechanical systems and models, and they had more time to explore these sliders compared to novices. We felt it was appropriate to ask experts to only perform one careful block because experts, being experts, were less likely to learn about the knob models during the trials. Furthermore, experts were asked to verbalize their current thoughts and strategies during the experiment (think aloud protocol [3]). These expert comments were transcribed by the experimenter for future qualitative analysis.

3.2.4 Results

Figure 3 illustrates how satisfied novice participants were with how closely each final knob rendering matched each of the five test knobs. Participants gave favorable satisfaction ratings for all test knob matchings [$M = 2.5$, $SD = 1.0$] for a range of 1-9 with 1 being most satisfied, but significant rating differences between the knobs were not observed.

Pairwise comparisons between the satisfaction ratings for the knobs were tested using a typical non-parametric test, a Wilcoxon Signed-Ranks test. Significant differences were found between:

- $\text{Knob}_{\text{high friction}}$ - $\text{Knob}_{\text{non-sine detents}}$ [$Z = 2.58$, $p < .01$]
- $\text{Knob}_{\text{high friction}}$ - $\text{Knob}_{\text{moderate detents}}$ [$Z = 2.17$, $p < .03$]
- $\text{Knob}_{\text{high inertia}}$ - $\text{Knob}_{\text{non-sine detents}}$ [$Z = 2.43$, $p < .015$]
- $\text{Knob}_{\text{high inertia}}$ - $\text{Knob}_{\text{moderate detents}}$ [$Z = 1.61$, $p < .10$]

These significant pairs are marked in Figure 3.

Figure 4 illustrates the relationships between expert participants, novice participants, and Haptic Camera parameterizations of the five test knobs. To better compare participant slider settings, the dependent axis of Figure 4 is scaled to the minimum and maximum stable operating levels for the haptic knob. These unit slider ranges from 0 - 1 map to the four parameter ranges listed in Table 4 (Use when interpreting Figure 4).

The two leftmost shaded columns of Figure 4 display slider settings for knobs without detents — $\text{Knob}_{\text{high friction}}$ and $\text{Knob}_{\text{high inertia}}$. The first (leftmost) column displays inertia parameter settings, M_{acc}, for these two knobs, and the second shaded column displays friction parameter settings, B_{vel}, for these two knobs. A_{pos} and P_{pos} are not displayed because they are only used exclusively for knobs with detents. For example, looking at the leftmost shaded column, circles, squares, and stars respectively represent the novice, expert, and automated (Haptic Camera) parameter estimates for inertia, M_{acc} of the two knobs $\text{Knob}_{\text{high friction}}$ and $\text{Knob}_{\text{high inertia}}$.

The four rightmost shaded columns of Figure 4 display slider settings for knobs with detents — $\text{Knob}_{\text{subtle detents}}$, $\text{Knob}_{\text{moderate detents}}$, $\text{Knob}_{\text{non-sine detents}}$. From left to right, these shaded columns display parameter settings for, M_{acc}, B_{vel}, A_{pos}, and P_{pos}.

Table 5 compares the Haptic Camera and expert participant parameterizations, along with their 95% confidence intervals. This table presents a subset of the same data as in Figure 4. As with previous tables, units are in mNm, rad, and s for torque, angle, and time, respectively.

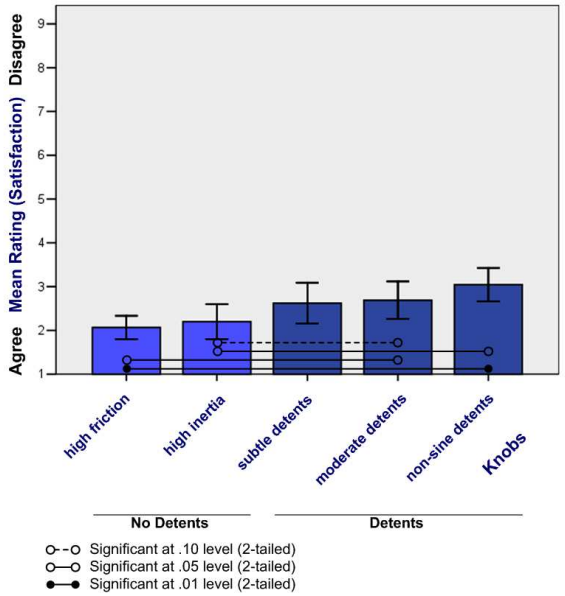

Figure 3: Novice ratings of satisfaction for how

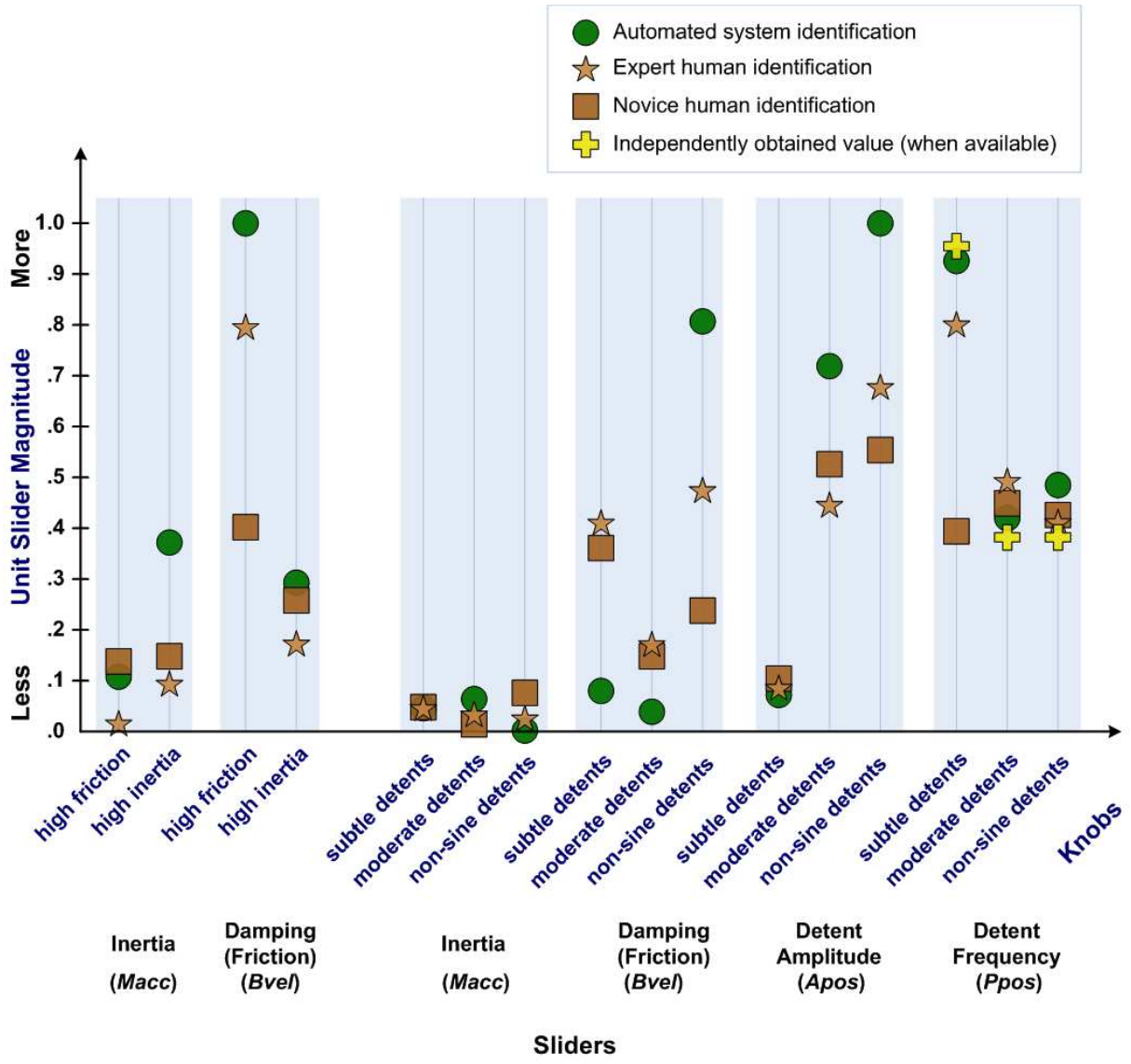

Figure 4: Comparisons of expert, novice, and Haptic Camera parameterizations for all five test knobs. Human parameterizations were performed in clusters, setting only the parameters present in those knobs.

Table 5: Comparison of Haptic Camera and Human Expert Dynamic Property Estimates (units are in mNm, rad, and s for torque, angle, and time, respectively)

Knob	***High friction***	***High inertia***	***Subtle detents***	***Moderate detents***	***Non-sine detents***
HC M_{acc}	.081	.28	.035	.049	.0018
EX M_{acc}	.01	.07	.033	.024	.02
95% CI	.011	.022	.024	.015	.021
HC B_{vel}	49	9.0	2.3	1.1	24

EX B_{vel}	24	5.1	12	5.1	14
95% CI	2.6	1.9	4.5	2.8	6.6
HC A_{pos}	-	-	1.1	11	130
EX A_{pos}	-	-	1.3	6.7	8.3
95% CI	-	-	.41	.91	1.5
HC P_{pos}	-	-	.22	.48	.41
EX P_{pos}	-	-	.20	.43	.50
95% CI	-	-	.00024	.057	.040

HC = Automated Haptic Camera Value
EX = Expert Participant Value

For the special case of detent frequency, independently obtained "gold standard" values can be easily calculated for the period by counting the number of "clicks" while manually turning the knobs with detents about one complete revolution. The number of "clicks" was also validated using visual inspection for $Knob_{moderate\ detents}$ and $Knob_{non\text{-}sine\ detents}$. Visual confirmation was not performed for $Knob_{subtle\ detents}$ because the confirmation could not be performed without permanently disassembling the mechanical knob sub-components. Table 6 lists the perfect "gold standard" values for these knobs beside the values obtained by the Haptic Camera and expert participants. "Gold standard" values for inertia were difficult to obtain because of the need to physically model a complicated inertia for the test knobs. Friction "gold standards" are even more difficult to obtain because surface material and geometrical properties between all moving parts need to be obtained. Calculating stick-slip frictional effects also impedes estimation of "gold standard" detent amplitude values. One would need to first calculate the geometries and material properties of the detents, then estimate the reaction torques generated as a user rotates through the detent. These other alternative estimation methods are tedious and error-prone, to be used as "gold standards".

Table 6: Comparison of detent estimates for knobs with detents

	Knob		
	Subtle detents	***Moderate detents***	***Non-sine detents***
Automated Measured (detents / rev)	29.1	13.2	15.2
Expert Measured (detents / rev)	25.1	15.4	12.9
Independently Obtained (detents / rev)	30	12	12

Table 7 lists the terms which each of the 15 novices recorded on their slider sticky notes. Data from experts is not described because slider settings were explained to the expert participants; so results of their sticky notes would be biased.

Table 7: Participant tags for dynamic knob properties

#	M_{Acc}	B_{Vel}	A_{Pos}	P_{Pos}
1	weight, "whoosh"	friction, heavy	bigness of detents	how many detents
2	spinny	stiffer, like moving through mud	really bumpy	small bumps, big bumps for fine tuning
3	spin faster	spin slower & stops	feeling bumps	spacing bumps
4	rotational force control	friction force control	control for a cycle of rotation	smoothness of rotation control
5	weight	friction	bump height	# of bumps
6	increase resistance; no brake	increase resistance; + break	increase stage effect	decrease stage width
7	smooth, but heavy	light & smooth; buttery	turning a smooth knob in definite steps	turning a knob with shorter steps in between
8	spin automatically	less resistant	clicks	faster
9	more friction	more friction; feels better than 1 [Macc]	more cranky	cranky
10	momentum	pudding	bump size	bump frequency
11	resistant spin	smooth spin	wobbly	knobbly
12	slingy	hard to turn	big clicky	clicky
13	resistance	sensitivity	smoothness	ditto (smoothness)
14	easy; little bumpy	touch, sticky, but smooth	stiff, large bumps	less stiff, smaller bumps
15	inertia	velocity control	amplitude of detents	frequency of detents

4 Discussion

Our discussion starts by comparing the quantitative haptic matching results between the Haptic Camera, experts, and novices. Next, qualitative data analyses are performed to provide a deeper understanding of the quantitative haptic matching results. The ability of novice participants to identify dynamic knob properties is addressed by examining these participants' sticky note memory aids. And, more complex perceptual attributes of knob dynamics are distilled from the experimenter's field notes collected from the expert participants' "think aloud" comments.

4.1 Human vs. Machine Performance

Many interesting relationships emerged between the parameterizations by human participants and the Haptic Camera. Our quantitative analysis focusses on relationships between the Haptic Camera and these experts because parameterizations by experts were more closely aligned with the Haptic Camera estimates and only experts performed a "think aloud" protocol.

Precise relationships between Haptic Camera and participant estimates were performed for detent frequency because independent "gold standards" could be calculated. Because the Haptic Camera's characterization employed the same algorithm for fitting detent period as for the other physical parameters, it is likely that the Haptic Camera reliably fitted the other dynamic properties to their respective models as well. However, we can only conjecture that these underlying mathematical models appropriately represent human-centered psychophysical responses to these knob dynamic properties. Both Haptic Camera and participant estimates must therefore be collectively considered if we are to understand how well the "feel" of the mechanical test knobs were captured and rendered. The following paragraphs use the user study results to compare these machine- and human-derived parameterizations.

Detent & damping confusion: Looking at the $\text{Knob}_{\text{subtle detents}}$ values for B_{vel} and P_{pos} in Figure 4, one can see relatively large differences between the human and Haptic Camera estimates. For this low-amplitude detent (see the A_{pos} values for $\text{Knob}_{\text{subtle detents}}$ in Figure 4), participants most likely had difficulty discerning whether the knob feeling was a frictional effect or a series of low frequency detents (the true knob mechanics). Referring to the $\text{Knob}_{\text{subtle detents}}$ column in Table 6, one can see that the Haptic Camera was able to (i) observe the detents as detents — not friction, and (ii) correctly estimate the detent frequency within a 3% relative error as compared with the average expert participant relative error of 18%. These errors could be calculated because independent "gold standard" values were available for detents.

Robustness to non-modeled detent properties: Examining frequency values for $\text{Knob}_{\text{non-sine}}$ detents in Table 6, one can see that human experts were better able to segment out (mentally set aside) backlash and non-linearities of $\text{Knob}_{\text{non-sine detents}}$ than was the Haptic Camera. In an effort to test a worst-case scenario, the latter used a model known a priori to poorly match $\text{Knob}_{\text{non-sine detents}}$ (refer to Equation 2). Meanwhile, the relative low frequency and high magnitude of the detents (see the A_{pos} values for $\text{Knob}_{\text{non-sine detents}}$ in Figure 4) likely aided the expert parameterization.

Inertia & damping confusion: The novice and expert participants often confused B_{vel} and P_{pos} parameters (refer to $\text{Knob}_{\text{high friction}}$ and $\text{Knob}_{\text{high inertia}}$ in Figure 4). This confusion could possibly be explained by the fact that both properties have an initial resistance component as one begins to turn a knob. Conversely, the Haptic Camera algorithm treats position-, velocity-, and acceleration-dependent parameters as equally difficult mathematical parameters to solve.

Participants may also have been confused by the ability to change mass with a slider. Prior research does suggest that people can become good at perceiving and dealing with changes in mass. Although dynamically changing mass is a foreign concept for most physical controls, people do experience change of mass in other everyday experiences. Learnt behaviors from these experiences may transfer well to active physical control use. For example, Turvey has studied one's ability to balance a half-

full glass of water in one's hand, and explored center-of-mass versus perceived length discontinuities for people holding different baseball bats [26]. Further research based on Swindells et al.'s [25] user studies using an experimental apparatus that could dynamically change center of mass could also be insightful.

Actual versus perceived satisfaction: The self-reported satisfaction ratings of Figure 3 illustrate interesting relationships between actual versus perceived performance. For example, participants were significantly more satisfied with their parameterizations of $Knob_{high\ friction}$ and $Knob_{high\ inertia}$ compared to $Knob_{moderate\ detents}$ and $Knob_{non\text{-}sine\ detents}$. Because $Knob_{moderate\ detents}$ had subtle detents that were often confused with frictional texture, mean satisfaction ratings that fall between those of knobs without detents ($Knob_{high\ friction}$ and $Knob_{high\ inertia}$) and knobs with detents ($Knob_{moderate\ detents}$ and $Knob_{non\text{-}sine\ detents}$) are consistent with other observations. The lower satisfaction ratings for $Knob_{moderate\ detents}$ and $Knob_{non\text{-}sine\ detents}$ could be due to increased cognitive load dealing with detents in addition to inertia and damping parameters. Additionally, the feel of $Knob_{non\text{-}sine\ detents}$ was impossible to match using the sliders because the underlying rendered physical model was known to differ from the actual physical model. Even though participants were able to deal with these model differences very well (e.g., see $Knob_{non\text{-}sine\ detents}$ frequency estimates in Table 6), participants may have felt more cognitive strain in the process. This result supports the need for appropriate affective design because it is an example where participants were dissatisfied even though they performed relatively well.

Absolute versus relative estimation: Comparing expert participants and Haptic Camera values for each of the knobs and parameters in Figure 4, one can clearly see agreement between the relative Haptic Camera/human relationships for individual parameters even when the absolute values found by the Haptic Camera and humans do not agree. That is, for a given parameter such as M_{acc} or B_{vel}, the ratio of [experts' value for $Knob_n$] / [experts' value for $Knob_m$] was similar to [Haptic Camera value for $Knob_n$] / [Haptic Camera value for $Knob_m$]. For example, looking at the damping scores, expert participants as a group did a good job estimating the relative damping levels between the different test knobs. Looking closely at the B_{vel} parameters for $Knob_{high\ friction}$ and $Knob_{high\ inertia}$, one can see that the Haptic Camera values for both knobs are similar ratios to the corresponding values provided by the expert participants.

This dominance of relative processing over absolute processing is consistent with visual psychology research, such as Snowden [20], and is generally consistent with current psychophysics theory such as Stevens' assertion that participants make judgements on a ratio scale [22].

4.2 Sticky Notes from Novice Participants

Analysis of novice sticky notes provides insight into the novice participants' ability to determine and understand fundamental detent, friction, and inertia renderings.

The labels summarized in Table 7 provide a strong indication that most participants were able to quickly and correctly identify the four sliders into appropriate categories — inertia, damping friction, detent amplitude, and detent frequency, respectively. For example, participant 10 used the terms "momentum" and "pudding", and participant 1 used the terms "weight 'whoosh'" and "friction, heavy" as labels for "inertia" and "damping". Although "whoosh" and "pudding" are not technical terms for inertia and damping, they are excellent non-technical, vernacular descriptions. Similar terminology could

greatly enhance accessibility and understanding to non-technical users of ubiquitous computing devices containing active dynamics.

Although less universal and specific, participant 11's terms "wobbly" and "knobbly" terms for amplitude and frequency of detents, respectively, indicate that this individual clearly understood the concept of detents. Only the labels from participant 9 induce serious concern that the participant did not adequately understand the effects of each slider. Participant 9 used the same label "friction" for both the friction parameter (B_{vel}) and the inertia parameter (M_{acc}). Participant 9 also used the same vague term "cranky" for both the detent amplitude (A_{pos}) and period (P_{pos}). Participant 13's labels also seem questionable since detent amplitude and frequency are both labeled "smoothness". Nevertheless, two or fewer participants out of fifteen having experienced confusion during the initial training phase of the user study is promising. More important is the suggestion that the previously mentioned confusion between inertia and damping (e.g., see Figure 4) is likely due to the complexity of the particular task, rather than the participants' lack of intuitive understanding of fundamental properties of physics.

4.3 Discussion of Field Notes from Expert Participants

Discussion of the field notes collected from sessions with the expert participants are organized according to several broad themes (field notes were not collected from novices).

Strategies: All the experts used a variety of grasping techniques on the haptic and test knobs to explore various dynamic properties. Initial coarse categorizations were typically performed with a whole-hand grasp of a knob, then finer single finger motions (usually with the index or middle finger) were used for more sensitive, refined judgments. When comparing damping and inertia, experts typically rotated the knob slowly at first to feel some velocity-based feedback, then they progressively made faster, more "jerky" motions to explore inertia. Another common technique for inertia estimation was spinning the knob as fast as possible, then timing how long the knob slid past one or more fingers lightly touching the edge of the knob.

Experts typically first categorized a test knob as "with detents" or "without detents". Next, experts tended to refine the rendered knob's detents (if present), then friction, and inertia were explored. In other words, an exploration strategy of position-, then velocity-, then acceleration-based parameters was most typically used. Experts would then iterate towards their final solution by tweaking whatever parameters seemed least correct. Experts iteratively refined their slider settings with frequent exploration back and forth between the test knob, rendered knob, and the physical sliders.

Experts also attempted to use visual cues from the spinning knob, but this strategy was (intentionally) quite difficult because all the knobs were fitted with uniform, white plastic caps.

Parameter interactions: When increasing the inertia, two experts stated that this made detents feel less noticeable. One expert elaborated by saying the physical interaction between inertia and detent amplitude "felt right". In other words, based on physics, one would expect detents to be less noticeable on knobs with higher amounts of inertia. These statements suggest that the interactions between different position-, velocity-, and acceleration-based effects occurred as expected based on fundamental laws of physics, but these physical properties were occasionally difficult for

even experts to mentally segment. One expert was frustrated because damping and inertia affected each other — even though this is the kind of interaction he should have felt.

These comments by experts suggest that segmentation of properties away from realistic physics could improve tool usability for designers of rendered or mechanical knobs for "real world" applications. For example, designers might more easily create a physically realizable model if they could manipulate a single parameter re-mapped to a combination of system model parameters. In other words, such an approach would not separate the user and system models when appropriate.

Physically non-realizable models may also be interesting in their own right. For example, a momentum-like parameter that does not interact with detents or friction could theoretically be rendered on a haptic knob even though such knob dynamics would be difficult, if not impossible, to create on a "real" mechanical knob.

Confidence: An area that did not improve participant confidence in their characterizations was the relation of the slider movement to the resulting effect on knob feel. An expert felt that the sliders did not seem to act in a linear manner, but the slider action was in fact linear. This statement suggests a conflict where a linear relationship in an engineering space may not be linear in a perceptual space. Non-linear slider mappings may therefore be more intuitive for parameter estimation, as suggested by Stevens' power law [22]. Also, two experts were unsatisfied with the "jittery" feeling on the rendered haptic knob when all sliders were set to their maxima. High inertia, high amplitude detents are technically challenging to render [11], and appropriately dealing with practical control issues is a significant barrier to haptic control adoption.

There were, however, unexpected confidence boosters too. One expert did not initially recognize the detents on $\text{Knob}_{\text{subtle detents}}$, but this expert was quickly able to identify subtle detents by rotating the knob at different velocities. The expert then adjusted the detent amplitude, A_{pos}, and damping, B_{vel}, parameters to create an appropriate rendering of $\text{Knob}_{\text{subtle detents}}$ on the haptic knob. If this expert was not confident in perceptually relating the appropriate physics-based properties using the damping and detent sliders, he would not have been able to make an appropriate rendering. Another expert also made the comforting comment that the angular differences between the haptic knob mounting and the test knob mountings did not interfere with parameter estimation. This result suggests a reasonable robustness of the data to the physical layout of the knobs.

Experts typically spent between two and six minutes adjusting the four sliders to match a single test knob. Experts would often switch between the rendered knob and test knob over a dozen times for each trial. This large amount of time and iteration per trial suggests the task was moderately difficult, and suggests that even the experts required significant effort to distinguish dynamic parameters, despite their eventual proficiency in accomplishing the task.

Validity: In addition to the previously described difficulties with stiffness and closed-loop feedback control, a primary validity-related problem was eradicating the sounds of clicks from the mechanical test and rendered knobs when experts were exploring detents (multimodal effects). Because the novice participants were not asked to think-aloud during their experiment trials, they were able to wear noise canceling headphones that reduced or eliminated this problem.

One expert experienced difficulty getting the amplitude setting of $\text{Knob}_{\text{subtle detents}}$ high

enough to be felt, but not too high. Conversely, two experts mentioned that the haptic knob did not feel stiff enough. These are common difficulties with almost all force-feedback technologies. These dynamic range issues are gradually being addressed within the haptics community through a combination of better mechatronics and better control algorithms. For example, greater stiffness could be obtained using haptic controllers with built-in braking mechanisms [18], or carefully timed bursts of force [7].

Finally, in terms of assessing how "real" the rendered knobs felt — as apposed to "simulated" — to these experts accustomed to haptic rendering, perhaps the most promising comments came from two experts who asked if the test knobs were a combination of mechanical and rendered knobs. Specifically, the feel of test Knobsubtle detents was described as "complex, sophisticated... like a haptic knob." Interestingly, two curious novice participants asked similar questions when informally chatting with the experimenter after completing their studies. This confusion between mechanical and rendered knobs is a strong indication that the quality, and therefore the validity, of rendered dynamic properties was reasonably good for at least some of the renderings. The expert's comment also suggest that haptic controls could potentially provide a richer, more "full-bodied" dynamic feel than what is possible with most mechanical controls.

4.4 Summary of Human vs. Machine Performance

User studies comparing haptic knob renderings for five mechanical test knobs were conducted by asking novice and expert participants to adjust four parameters of a rendered knob to match the feel of a test knob. Similar relative detent, friction, and inertia parameterizations were observed by human expert and Haptic Camera estimation methods. Independent "gold standard" checks of detent frequencies for $Knob_{subtle\ detents}$, $Knob_{moderate\ detents}$, and $Knob_{non\text{-}sine\ detents}$ with the Haptic Camera averaged 3.0%, 9.5%, and 23.5% relative accuracies, respectively, whereas human experts averaged 17.7%, 24.8%, and 7.2%.

These data, combined with data for damping estimation, suggest that human ability to make accurate and confident parameterizations were more robust to irregularities such as unmodelled non-linearities and backlash compared to an automated test procedure. Conversely, the Haptic Camera significantly outperformed human experts (and human novices) when an appropriate physical model was used. For most knobs, such models are relatively easy to choose, and can be tested for accuracy using techniques such as confidence interval calculations on final curve fitting results (e.g., see Table 5).

These studies help demonstrate that the Haptic Camera apparatus can effectively capture knob dynamics as perceived by a human.

5 Implications for Design

We conclude with a list of high-level design implications resulting from our validation studies.

Moderate friction and inertia is best: Similar to the findings by Knowles and Sheridan for mechanical knob friction and inertia [6], our participants preferred moderate inertia levels around 0.1 mNm / rad/s^2 and viscous damping around 10 mNm / rad/s instead of more extreme values.

Current rendering qualities are good enough: Using our state-of-the-art haptic knob, expert and novice participants were able to match acceleration-, velocity-, and position-dependent physical parameters within previously established tolerances [6]. Through economies of scale and modest

technological advancements, dynamic renderings could be effectively incorporated into consumer products.

Humans adapt to relatively large rendering model inaccuracies. Human participants effectively matched detent amplitude and period of $Knob_{\text{non-sine detents}}$ even when the underlying detent rendering model was known *a priori* to significantly deviate from mechanical test knob. In this case, human observers were better able to adapt to physical model inconsistencies such as backlash and non-sinusoidal detents better than our automated capture process.

Use inertia sparingly: Novice and expert participants had difficulty discerning inertia from friction. Thus, designer should minimize using inertia as a distinguishing effect. Nevertheless, participants *preferred* inertia effects over friction and detent effects.

Use subtle detents as textures: Subtle detents, such as $Knob_{\text{subtle detents}}$ used in our studies, were often confused with subtle friction effects and described as more of a textural effect compared to the other detent effects. Consequently, subtle detents could be used in lieu of friction effects in some implementations. This observation is practically significant because actively rendering detents is often easier, cheaper, and more stable compared to rendering higher order effects such as friction.

Human observers are very poor at estimating absolute values: Even on the knobs with only 12 detents / revolution, neither novices nor experts counted the number of clicks / revolution. All reports were estimated. An interesting follow-up study could test if human matching performance improves with the addition of visual feedback of the detent effects.

Confusion between friction & inertia with participants (i.e., even though automated capture and rendering worked reasonably well), participants confused friction and inertia.

6 Conclusions

Participants were able to keep track of 4 independent dynamic parameters (1 acceleration, 1 velocity, and 2 position) while altering the dynamics of a force-feedback knob. The captured parameters of the 5 mechanical test knobs were found to agree with parameterizations by novice and expert participants, and when available, with "gold standard values". For example, detent period could be determined by counting the number of clicks per revolution. This "gold standard" provides insight into the quality of all the automated Haptic Camera and expert human parameter estimates. For the two "appropriate model" and one "inappropriate model" characterization tasks, the Haptic Camera algorithm estimated detent period to 3.0%, 9.5%, and 23.5% relative accuracies, respectively, whereas human experts averaged 17.7%, 24.8%, and 7.2% relative accuracies, respectively.

The Haptic Camera algorithm treated the period parameter in a similar way to position-, velocity-, and acceleration-based parameters, but humans have increasing difficulty exploring position-, velocity-, and acceleration-based parameters.

These results suggest that an automated Haptic Camera approach based on an appropriate physical model (i) performed good quality characterizations below the suggested thresholds suggested by previous research such as Knowles and Sheridan [6], and (ii) typically outperformed expert human observers.

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