Aarnio: Passive Kinesthetic Force Output for Foreground Interactions on an Interactive Chair

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ABSTRACT

We propose a new type of haptic output for foreground interactions on an interactive chair, where input is carried out explicitly in the foreground of the user's consciousness. This type of force output restricts a user's motion by modulating the resistive force when rotating a seat, tilting the backrest, or rolling the chair. These interactions are useful for many applications in a ubiquitous computing environment, ranging from immersive VR games to rapid and private query of information for people who are occupied with other tasks (e.g. in a meeting). We carefully designed and implemented our proposed haptic force output on a standard office chair and determined the recognizability of five force profiles for rotating, tilting, and rolling the chair. We present the result of our studies, as well as a set of novel interaction techniques enabled by this new force output for chairs.

CCS CONCEPTS

• **Human-centered computing → Haptic devices**.

KEYWORDS

Haptics, interactive chair, passive kinesthetic force output

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1 INTRODUCTION

Activities when seated (e.g., typing or gaming) is common in daily life, and has motivated research on interactive chairs in many application areas, such as work efficiency and ergonomics [4, 17, 24, 32, 36], driving safety [3, 9, 11, 23] and entertainment [12, 20, 27, 31]. Within this usage context of interactive chairs, haptics as a primary output mechanism have been developed mainly for background interactions [19], where input to the chair is carried out behind a user's conscious awareness (or *implicit input*). Examples for such input include leaning sideway on the chair due to a bad sitting posture. Haptics (e.g., vibrotactile) was used to remind the user to change the posture [17]. However, haptic output for foreground interactions [5], where input is carried out in the fore of the user's consciousness (or *explicit input*, [2, 28]), remains unexplored. This class of haptic output is tightly coupled with input and can be a valuable addition to the existing haptic output to improve user experience and enabling new applications on interactive chairs.

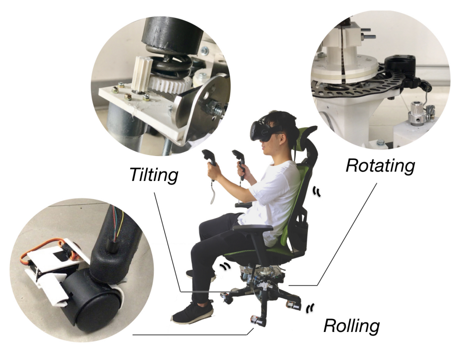


Figure 1: Aarnio modulates the resistive force of rotating, tilting and rolling an office chair for new applications.

In this work, we propose passive kinesthetic force output [18] for user's explicit input via rotating, tilting, and rolling the chair. (Figure 1). This type of output can restrict a user's motion for novel interactions on a chair. For example, the seat can be hard to rotate or locked in place to restrict user mobility in a first-person VR shooting game, mirroring how severely the player's vehicle is damaged. Alternatively, the backrest can be hard to recline to convey a message to the user (e.g., hardness indicating the time remaining until the user's next meeting). This way the user does not need to interrupt the primary task involving both hands, such as eating, to interact with a phone calendar. Since the motion is ambiguous about whether the user is using technology or just recline backward, this type of interactions can be less interruptive to other people in a social event, such as a meeting, where checking the phone repeatedly may be socially inappropriate. This type of haptic output extends and maps to natural force feedback a user already receives when rotating the mechanical joint of a chair (e.g., if a chair does not roll properly, the assumption is that a wheel(s) could be broken), thus, can be natural and easy to understand.

We modulate the natural resistive force of the mechanical joints of the chair for output, and demonstrate our approach through Aarnio, a proof-of-concept prototype with the three interaction techniques selected based on user preferences and implemented using carefully designed braking and tension controlling systems. With our prototype, the resistive force of rotation is modulated using a disc brake on the shaft of the seat. The resistive force of rolling is modulated using servo motors to toggle the brake handle of the caster wheels. Finally, the tilt tension of the backrest is modulated by rotating the tension controller of the chair using a gear motor. Our system can also track the moving distance of rotation, tilting, and rolling, allowing varying types of resistive force profiles to be rendered on the chair.

We designed five force profiles per rotation, tilt, and rolling and tested their recognizability via three controlled user studies with 12 participants. These profiles were evaluated with or without cognitive load to understand how real-world scenarios would affect the perception of force profiles. The results showed that participants could distinguish between the force profiles with 93.75%, 87.3%, and 93.0% accuracy for rotation, tilting, and rolling, respectively. Finally, we describe a wide range of application scenarios to demonstrate the interaction design space. As an initial exploration of this concept, our paper focuses on the potential interactions of the proposed force output. Although more studies on the utility for each application are needed as future works, we hope to spark new ideas and directions for this area.

The main contributions of this paper include: 1) passive kinesthetic force output for foreground interactions on an interactive chair; 2) a prototype that can modulate the resistive force of rotating, tilting, and rolling the chair; 3) the results of user studies evaluating the recognizability of the force profiles designed for the three types of interactions.

2 RELATED WORK

Chair Input

Implicit input. Input on interactive chairs has been widely studied, with much of the work focusing on sensing user's sitting postures [3, 6, 10, 12, 24, 25, 27, 32, 35, 36]. For example, Tan et al. [24, 35, 36] used pressure sensors over the seat pan and backrest to capture the user's sitting postures. Other techniques included capacitive sensing [3, 27] and RFID [32]. The posture data of these works was used to improve work efficiency and ergonomics, driving safety, and entertainment. ChairMouse [8] used the rotational angle of the seat pan to infer the user's facing direction to automatically move a mouse cursor between multiple monitors. All these works use implicit input for background interactions [19] on an interactive chair with no haptic feedback via the chair itself.

Explicit input. Unlike implicit input, explicit input for foreground interactions [5] on interactive chairs has only been explored recently. For example, Beckhaus et al. [2]'s system allows the user to rotate or tilt the seat to control video games. Probst, et al. [28] studied tilting, rotating, and bouncing the seat to interact with a computer. Their research shows that the primary benefit of explicit input via the chair is in casual and occasional situations, where interrupting people's primary task involving both hands is not preferred. For both works, feedback for the chair input was provided via visual clues shown on a computer monitor with no haptic output.

Chair Output

Haptics is the primarily output mechanism on interactive chairs with research primarily focusing on vibrotactile output [20, 23, 31]. For example, Morrell and Wasilewski [23]'s car seat uses a grid of vibrotactile actuators on the backrest to inform the user about the location of the vehicles outside the car. Vibrotactile grid on the backrest has also been used to create immersive gaming experiences [20, 31] and for notifications [38]. Pressure output has been used for notification via the chair as well [39]. Fels, et al. [9]'s haptic car seat tilts to inform the driver about the relative distance and velocity to the objects outside the car. Active force feedback on a chair can be used for guidance [14] or enhancing immersion [7, 29] for VR experiences. BodyPods [25] uses LED lighting patterns to show sitting postures of the occupant to a remote person. Beyond chairs, haptic feedback has also been used on other furniture, such as door knobs [22] and floors [37], to communicate information to a user. However, within existing research, little has been done to examine passive force feedback for explicit user input for general foreground interactions [5] on a chair.

Resistive Force Feedback

Resistive force feedback has not been previously studied on interactive chairs. While systems like haptic knobs [1, 16, 33, 34] utilize resistive force to simulate mechanical knobs, little research has been conducted to study such feedback for general interaction tasks in everyday scenarios. Our research was inspired by Frictio [18], a smart ring that can provide passive kinesthetic force output for rotational input on a ring. The device generated six force profiles that could be distinguished by study participants with 94% accuracy. This type of feedback can be used for eyes-free interactions for on-demand information acquisition or games. SqueezeBlock [15] uses a similar concept, allowing a user to acquire information by feeling different types of virtual spring profiles when squeezing a phone-shaped device. In this work, we explored passive kinesthetic force output on an interactive chair, which introduces many engineering and human factors challenges, as well as interesting new applications and scenarios.

3 KINESTHETIC FORCE FEEDBACK

There are primarily two types of haptic outputs: *tactile* and *kinesthetic*. Kinesthetic output relies on the feeling sensed from muscles, tendons, and joints. As such, the resistive force feedback discussed in this paper is a type of kinesthetic output. In contrast, tactile feedback relates to the cutaneous senses, coming from stimulating the mechanoreceptors within the skin. Vibrotactile output is an example of tactile feedback. These two types of haptic output complete but do not replace each other. For example, resistive force output may restrict a user's motion whereas vibrotactile does not. As such, applications for them can be very different.

The kinesthetic force output can be either *active* or *passive* from user's perspective [30]. Passive force output resists human motion whereas active force output induces human motion [13]. Applications suitable for these two types of force output are also different. For example, passive output can be more suitable for providing output that directly relates to the user's explicit input. Alternatively, active output may be more suited for providing notifications or other 'asynchronous' information [21] that is of interest to the user. Our work focuses on *passive kinesthetic force output* for foreground interactions on a chair.

4 INTERACTION DESIGN SPACE

We briefly discuss the interaction design space of the proposed passive kinesthetic force output. We studied this output channel for foreground interactions, defined by Buxton as "activities which are in the fore of human consciousness — intentional activities" [5]. To demonstrate the idea and address as many of the possible interactions on an interactive chair, our discussion is centered around a swivel office chair, which has five major components: seat, backrest, armrest, caster, and headrest. This type of office chair is common in work or home environments, where we conducted this research. All the components are moveable around the corresponding joint in one or multiple degrees of freedom — including *pitch/roll/yaw* or *x/y/z* in its local coordinate system — to facilitate work or comfort (Figure 2). Since our goal is to demonstrate possibilities rather than exhaust the entire space, we leave the other types of chairs (e.g., knee chair) outside the scope of this discussion.

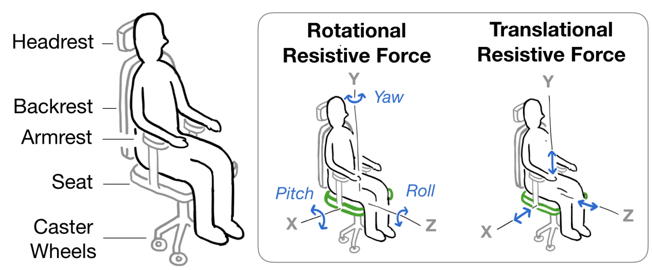


Figure 2: Illustration of the possible DOFs for the seat but is applicable to the other components.

Seat. Rotating the seat (yaw) has been used in previous research as an explicit input mechanism to provide control to computer applications or games [2, 28]. However, haptic feedback was not a focus of those works. When the seat of an office chair is rotated, there is a natural frictional force that is felt by a user. But during everyday use, this force is often ignored due to adaptation [26]. In cases when something goes wrong (e.g., the shaft of the seat is damaged), unusual haptic feedback can be felt by a user, suggesting potential directions for the user to diagnose the chair. In this context, haptic feedback has already been used on a chair to suggest certain events. In addition to rotation, the height of a seat can be adjusted for comfort. This degree of freedom was also studied in prior work (e.g., [28]) as an explicit input mechanism to control a computer, but no haptic feedback was developed. Additionally, the seat of some office chairs can be slid (translation in the y axis) or tilted forward/backward (pitch) for comfort.

Backrest. The backrest is tilted when a user reclines backward, and consequently a spring force can be felt which is unique to the backrest. Tilting a chair has been used for explicit input in prior research (e.g., [28]) but haptic feedback for tilt has not been studied. Tilt tension of the swivel chair can be adjusted by manually turning a tension controlling knob under the seat. Turning the knob clockwise compresses the spring that holds the backrest, increasing tilt tension and decreasing tilt distance. When the knob is at the end of its counter-clockwise direction, the spring is in its natural length, making the backrest easiest to tilt, offering the longest tilt distance. Tilt angle can be locked on some chairs, which provides opportunities for interesting feedback techniques. The height of the backrest can also be adjusted on some chairs to personalize lumbar support, but it can be hard to use for explicit input, especially when a user is seated.

Armrest. The armrests of an office chair are adjustable for height (translation in the z axis), distance to the user's body (translation in the x axis), and orientations (yaw). Like the seat, a natural mechanical haptic feedback can be felt by the user when the armrest is moved. Such haptic feedback can be modulated for output for interactive tasks.

Headrest. The headrest of the Swivel chair can be tilted (pitch). On many other chairs, its height can also be adjusted. Thus, the joints of the headrest can be augmented with passive kinesthetic force feedback for output.

Caster. When a chair is rolling on the floor, a natural force of friction from the wheels can be felt by a user. When something unusual happens (e.g., wheels are broken), this haptic feedback may change dramatically as the chair may become harder to move. It can be felt and interpreted by a user to find the source of the issue. Thus, this type of haptic feedback is already being used to inform the user about certain information. Modulating the resistive force from the wheels can be used for output for interactive tasks.

Aside from providing feedback in response to a user's explicit input, there are situations where movement of a chair component occurs as a consequence of a non-input task (e.g., turning the seat/body to a nearby person to start a conversation). In these situations, the chair can still provide haptic output despite a user's intention. This way, the user might still capture the haptic output, and this can be useful for communicating non-urgent information, requiring no immediate reaction from the user (e.g., a reminder for checking today's schedule). Accessing information using this way is unplanned but can be a useful addition to the ones discussed earlier or active output (e.g., notification).

To summarize, all the discussed components and movements can be useful for chair interactions. Within the scope of this research, we were interested in studying a small set among the numerous possibilities that holds the most potential to demonstrate the usefulness of the proposed passive kinesthetic force output. This motivated our informal study.

5 INFORMAL EXPLORATORY STUDY

The goal of this informal exploratory study was to elicit initial user preferences on the discussed chair interactions. The result of this informal study allowed us to prioritize the most promising ones to develop and study further.

Participants and Task

We recruited 15 students and office workers (3 females, aged between 22 - 26). We began by explaining the study goals and we used a swivel office chair as a probe to encourage imagination. Participants used the same chair in their work environments. Next, they were asked to sit on the chair near a desk, as if working in their own office or lab. Participants were shown all possible chair movements in sketch form (similar to Figure 3). Given these examples of implicit interactions (derived from the literature), they then responded with a 'YES' or 'NO' as to whether they prefer to use each of the six degrees of freedom (e.g., pitch/roll/yaw and translation in the x/y/z axis) of the seat, backrest, headrest, armrests, and caster for interactive tasks, with respect to their *physical effort* during input. We included movements that appeared difficult to perform (e.g., pitch the headrest) for inclusiveness. We used binary responses instead of a Likert scale, as the approach avoids tendency errors from a relatively long survey. In addition to explicit interactions, we also asked participants to respond to situations where feedback received is unplanned due to their unintentional body movements (or implicit input).

Results

Amongst all possibilities, only a few were considered useful for input. Figure 3 shows the aggregated results from our participants. Rotating, tilting and rolling were top ranked and the most well-balanced between explicit and implicit input.

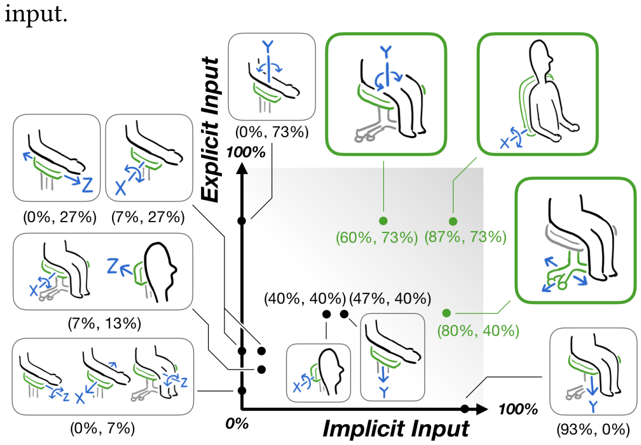


Figure 3: User preferences categorized by explicit & implicit input.

Over 65% of the participants preferred tilting the backrest for both explicit and explicit input. Participants reported that the action was "*physically effortless*" and "*natural to perform in workplace.*" Rolling the caster is less preferred for explicit than implicit input. This is because it is common for the user to move the chair around for comfort but chair displacement during work may impact work. In contrast, rotating the seat was less preferred for implicit than explicit input because participants found it less likely to rotate the seat without intention. Rotating the armrest in the yaw direction was considered suitable only for the explicit input, as participants "*normally rest my hands on the armrest without performing any actions*" (P8). Participants commented that it was important to have an automatic mechanism to rest the position of armrests after the interaction because they otherwise had to set the armrests back to the comfortable positions. In contrast, the vertical movement of the seat was regarded as suitable for only implicit input. It is a natural way to acquire haptic information at the moment of sitting on the chair. Participants commented that "*it could be pretty awkward to compress the seat for explicit input*". This is different from Probst, et al.'s study [28] because our office chair does not have a spring strut. None of the remaining interactions were preferred by over half of the participants on either input style as they were found hard to use. We thus chose to focus on rotation, tilt, and rolling in this work. Note that the study results only worked for prioritizing chair interactions in terms of *physical comfort* for input and cannot be generalized outside the scope of this study.

6 AARNIO PROTOTYPE

Based on the results of the informal study, we created a prototype to demonstrate the proposed haptic output. Our prototype was created by augmenting the backrest, seat, and caster of the Swivel office chair. We extended the natural resistive forces of the joints of the chair using carefully-designed braking and tilt tension controlling systems.

Rotation (seat)

Figure 4: Disc brake modulating the resistive force of rotation.

We augmented the shaft of the seat with a braking system to restrict its rotational motion. The original gas lift was replaced by a custom-made steel shaft for the sake of simplicity. Applying a brake directly on the shaft did not create enough resistive force. To overcome this challenge, we used a bicycle disc brake instead, which created a longer lever arm to generate braking forces strong enough to lock the seat firmly in place (Figure 4). The disc brake has a rotor diameter of 160 mm, welded on the shaft. The caliper of the disc brake is fixed on the base of the chair via a 3D printed mount using bolts and nuts. A ball bearing was used between the rotor and the caliper mount to provide smooth rotation. The disc brake can be engaged by pulling the caliper cable using a DC motor (GB37Y3530-12V-90EN, DFRobot), also mounted on the base of the chair. The motor has torque of 0.85 Nm and speed of 146 RPM. It can fully engage the break in 50 ms. The motor was controlled using a Motor Driver (TB6612FNG, SparkFun) that was connected to an Arduino Uno board and communicated with a laptop computer via USB. Finally, we installed a gyroscope (MPU-6050, InvenSense) on the backrest to track the rotational angle of the seat. This information is needed for force profiles, associating the amount of resistive force with the rotational angle of the seat (e.g., Ramp-Down).

Tilt (backrest)

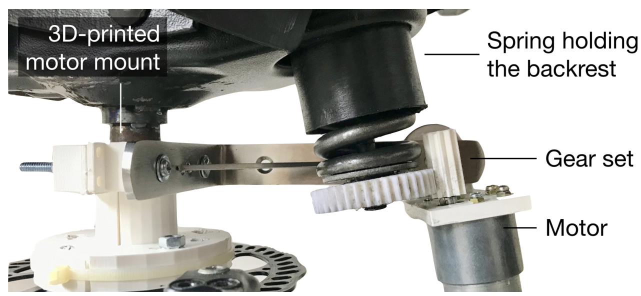


Figure 5: System modulating the spring tension of tilting.

We created a tilt tension controlling system using a DC motor (ST37A-5A6K2-12-18, Silent Industry) connected to the tension controller via a custom gear set. The gears were used to increase the torque of the motor (4.70Nm, 117.5 RPM) to rotate the tension controller (Figure 5). With this setup, we were able to increase the tension from the lowest (spring not compressed) to the highest (spring completely compressed) in about 1.4s, and vice versa. Ideally, tension needs to be changed instantly, but the current implementation works well for our study and demo applications as the designed force profiles do not require instant change of the tilt tension. We used a magnetic encoder to estimate spring tension according to how many times it rotates the tension controller. It was mounted on a steel frame, connected firmly to the rotor of the disk brake using screws and a 3D printed mount. The gear of the motor was 3D printed 25 mm long to leave space for the one on the tension controller to travel when it rotates. The same gyroscope on the backrest was used to track the tilt angle of the backrest. This information is needed for force profiles like Tension Ramp-Down.

Rolling (caster)

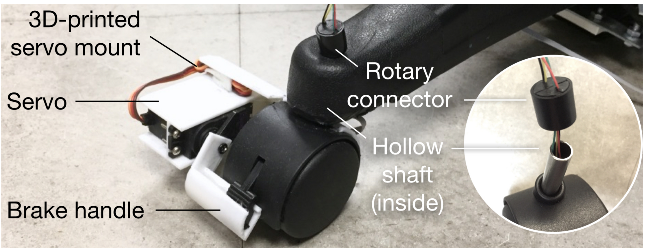


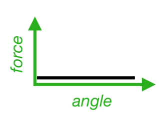
Figure 6: Wheel brake modulating the resistive force of rolling.

We created a braking system for the caster using servo motors (MG996R, TowerPro) to toggle the brake handle of wheels. The motor was mounted on the side of the wheel using a 3D printed case. To ensure that the wires do not get tangled due to the wheels spinning horizontally, we replaced the original solid shaft using a hollow one (Figure 6). This allowed the wires to pass from inside the shaft through a rotary connector. The servo motors were controlled using an Arduino Uno board and communicated with the same laptop. Our tests on a tile floor showed that when the brake is engaged on at least two of the five wheels, a clear resistive force can be felt by a user when rolling the chair in a seated position. The chair can be locked in place on when all the wheels are locked. This enables varying resistive forces for rolling. We also installed an optical flow sensor from a mouse under the caster to track the moving distance of the chair to enable new profiles like Click. The mouse sensor was connected to the same Arduino board as the servo motors.

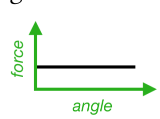
7 FORCE PROFILES

To demonstrate the capabilities of the proposed passive kinesthetic force output, we designed and implemented five force profiles (inspired by SqueezeBlock [15]) for each of the three chair interactions supported by our prototype. We also tested the profiles in a pilot study to ensure user safety.

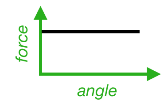
Profiles for Rotating the Seat



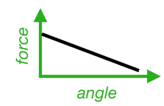
Natural Resistance. With this profile, no resistive force is applied by the haptic system. The only force felt by a user is the natural light friction (1.75 Nm) when rotating the seat.



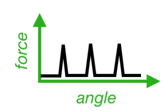
Strong Resistance. It represents a resistive force that requires effort from the user to overcome when rotating the seat. The user can associate the resistive forces with a certain event. For example, different events or information can be encoded in the force feedback, with a light resistive force representing one event, and a stiffer force representing another. Our implementation resists a torque of 8.75 Nm (in 25 ms) on the seat via the disc brake.



Lock. With lock, the seat is locked in place, preventing it from being rotated. We implemented the Lock for rotation by fully engaging the disc brake (in 50 ms), which resists a torque up to 26 Nm. Lock can also be triggered after a certain distance of movement. For example, the seat can be locked after being rotated for a certain amount of degrees. This leading distance can also encode information.



Ramp-Down. The braking force applied to the disc brake can decrease as the seat rotates. As a result, the user feels the seat becoming easier to rotate the more they rotate it. Different information can be encoded and conveyed to the user by changing the slope or duration of the ramp. Additionally, this profile can be used to assist with fine-grained motor control for continuous input. In our implementation, Ramp-Down starts with a resisting torque of 26 Nm, and gradually decreases the braking force to that found with the Natural Resistance profile as the user rotates the seat up to 45 degrees.



Click. It alternates between natural and strong resistance and can repeat. Different information can be encoded through the number, density, force, as well as the width of the click. Alternatively, this profile can be used to reduce attention on tasks requiring fine-grained motor control. For example, discrete targets can be located inside two adjacent clicks to prevent the user from slipping off the target when rotating the seat. In our system, the disc brake is engaged in Strong Resistance when the seat rotates a certain degree (e.g., 5°), and rapidly disengages once reaching peak torque.

Profiles for Rolling the Chair

Like rotation, rolling also modulates the braking force, thus the force profiles for rolling are the same, except that we locked the wheel(s). There are other facts that may affect the amount of resistance force felt by the user, including the type of floor, location of the locked wheel(s), and orientation of the locked wheel(s), among which the type of floor (e.g., hardwood, tile, or carpet) affects the resistive force the most. For example, it is harder to roll the chair on carpet than tile or hardwood. Our profiles were designed and implemented for flat tile, commonly used in schools and office buildings from where this research was conducted.

The location of the locked wheel(s) may also affect resistive force. Our test with different combinations of two locked wheels revealed a force range between 20.6 to 28.4 N, not big enough for the difference to be notable. So we randomly chose the wheels to locked. Note that the orientation of the wheels may not align with chair's rolling direction, so they spin (often with the caster) horizontally at the beginning when the chair starts to roll, until all the wheels align with the chair's moving direction, which takes about 12 cm maximum on our chair and feels like crossing a smooth bump in a lateral direction. To avoid the "bump" from mixing up with our force profiles, we only start rendering our force profiles after 12 cm. So, the amount of resistive force reported below were measured with all the wheels aligning with the chair's moving direction. The figures for the force profiles are the same as those for rotation, so we do not repeat them here.

Natural Resistance. No wheels are locked for this profile. The average resistive force measured was 6.9 N.

Strong Resistance. Our chair resists an average force of 25.5 N by locking two randomly selected wheels.

Lock. This profile locks all five wheels. It provides an average resistive force of 42 N. Lock can also be triggered after the chair is rolled a certain distance.

Ramp-Down. It starts with four locked wheels (38 N), and gradually decreases the braking force by releasing the wheels (one per 60 mm) until all the wheels are unlocked.

Click. It locks and releases three randomly selected wheels for every 60 mm the chair is rolled.

Profiles for Tilting the Backrest

Force profiles for tilt modulates spring tension instead of braking force. According to Hooke's Law, the actual force that is needed to tilt the backrest increases with the increase of the backrest's tilt angle (or the spring's compression distance). This is different from rotation and rolling, where the resistive force is relatively constant. However, from a user's perspective, the effort needed to tilt the backrest decreases once it exceeds a certain tilt angle, where the body weight or gravity starts to push the backrest downward.

Minimum Tension. The spring is not compressed, in which case spring tension is the lowest. Therefore, the user can initiate tilt easily with the least effort (73.3 Nm).

Low Tension. The spring is compressed 30% of its normal length, thus requiring more effort (84.3 Nm) from a user to initiate tilt compared to Minimum Tension.

High Tension. The spring is compressed 60% of its normal length, thus requiring the user to spend more effort (97.1 Nm) to initiate a tilt compared to Low Tension.

Maximum Tension. The spring is compressed its maximum distance. The backrest is fixed in a straight-up position, resulting in almost no ability for the user to tilt.

Tension Ramp-Down. Spring tension decreases with the increase of the backrest's tilt angle. In our implementation, Tension Ramp-Down starts with 90% spring tension (108 Nm) and decreases 30% every 5°. Our pilot study confirmed that users felt that the effort needed for them to recline decreases significantly.

8 USER STUDIES

We considered it important to understand whether the force profiles are recognizable by users, with the answer determining whether this new output channel can be effectively used for various application tasks. Thus, our goal for this study was to examine how well participants could perceive and distinguish the proposed force profiles using our implementation. We conducted three studies one for *rotation*, *tilt*, and *rolling*. The participants, apparatus, procedure, and design were the same for the three studies.

Participants, Apparatus and Task Conditions

Figure 7: The study setup.

We recruited 12 students and office workers (4 females), between the ages of 21 and 26, in our study. Participants were asked to sit in our prototype in front of a desk, where a 27-inch computer monitor was used to display an experimental user interface (Figure 7). They held a numeric keypad for input. Following the instructions shown on the monitor, participants were asked to identify which force profile was being presented. In half of the trials, participants also performed a secondary task to induce cognitive load, diverting their attention from the force pattern identification task and simulating scenarios such as interacting with the chair when chatting with someone, working on a laptop, or playing a video game. For the cognitive task, we used a modified Stroop test similar to [18], where the name of a color was shown in text rendered using a random font color. For example, the word "blue" was shown using a red font color. The text and color were rendered randomly from a pool of five candidates (e.g., Red, Yellow, Blue, Green, and Black) with a 2 second interval. During the task, participants were asked to count how many times a match occurred between the text and font color. To ensure the two tasks were performed simultaneously, participants were asked to maintain an accuracy above 90%. The percentage of correct responses to the cognitive task was shown on the monitor.

Each study included the five force profiles designed for the corresponding interaction. Most profiles, except *Click* and *Tension Ramp-Down*, were expected to be felt immediately after participants attempted to move the part. *Click* for rotation and rolling was rendered at every 5°for rotation and every 60 mm for rolling. The positions were determined by a pilot study, where a single clutch of these two movements exceeded these distances. Similarly, tilt required some leading distance to allow users to perceive the profile. During the experiment, participants wore noise cancelling headphone to block the noise generated by the motors. The software was programmed in Unity3D, running on a Windows laptop.

Procedure

During a trial in a study, participants were asked to either recline backwards, rotate the seat in a clockwise or counterclockwise direction, or roll the chair in one of the North, East, South, and West direction to feel a force profile. A force profile could be tried as many times as participants wanted until they were confident about reporting what it was. However, they were not allowed to feel the profile in a reversed the motion (e.g., rotating the seat back). To feel the force profiles again, participants pressed a keyboard key, which disengaged the haptic system, allowing the moving parts to be returned to their starting position. Participants then pressed the same key to engage the haptic system and tried the force profile again. Once completed, participants pressed the Enter key to finish the trial. They verbally told the experimenter which force profile was felt. Pressing the Enter key again began the next trial. In the condition where the cognitive load task was presented, participants performed the two tasks in parallel. There was no restriction on how the chair could be rotated, tilted, or rolled.

Prior to each study, participants were shown the Aarnio prototype and how it worked. They were allowed several practice trials in each study condition to familiarize themselves with the device and force profiles. Participants filled out a post experiment questionnaire upon completing a study. They indicated subject ratings for the recognizability of the force profiles using a continuous numeric scale (1: *very hard to recognize*, 7: *very easy to recognize*). Decimal ratings like 3.8 were permitted. Each study lasted approximately 60 minutes.

Experimental Design and Measures

Each study employed a 2×5 within-subject factorial design. The independent variables for rotation and rolling were Cognitive Task (*Cognitive Load* and *No Load*) and Force Profile (*Natural Resistance*, *Strong Resistance*, *Lock*, *Ramp-Down*, and *Click*). Independent variables for tilt were similar except that Force Profile included *Minimum Tension*, *Low Tension*, *High Tension*, *Maximum Tension*, and *Tension Ramp-Down*. Cognitive Task was counter-balanced among participants. During each trial, participants performed tasks in one of the Cognitive Task × Force Profile combinations. The experimental design for each study was thus $2\ Cognitive\ Tasks \times 5\ Force\ Profiles \times 8\ Repetitions \times 12\ Participants = 960\ trials$. Studies were presented in a random order and participants finished one study per day.

Dependent measures for the three studies included the profile recognition accuracy (i.e., the number of correctly identified force profiles), the response time of the last attempt (i.e., the time elapsed from the start of the force profile to the depressing of the Enter key), and the number of attempts required to identify each force profile. The response time for *Click* was measured from the moment when the force was rendered.

Results

The data were analyzed using repeated-measures ANOVA and Bonferroni corrected paired t-tests for pair-wise comparisons. Average movement distance for rotation, tilt, and rolling excluding Lock and High Tension is 47.3°(*SD*: 19.2), 20.9°(*SD*: 8.3), and 50.9 cm (*SD*: 32.6).

Profile Recognition Accuracy

Rotation. The average accuracy across all conditions for rotation was 93.8%, suggesting that the force profiles were relatively easy to recognize. There was a significant effect for Force Profile ($F_{2.83,31.14} = 5.68$, $p < 0.05$) but no significant effect for Cognitive Task ($p = 2.82$). *Lock* and *Click* received the highest accuracy, while *Ramp-Down* received the lowest (Figure 8). Post-hoc pairwise comparison found the only significant differences were between *Ramp-Down* and *Lock*, *Click*. *Ramp-Down* is confusing because the resistive force starts strong, which can be confused with *Strong Resistance* or *Lock*, and ends weak, which can be confused with *Natural Resistance* (Figure 9). All profiles aside from *Natural resistance* have a period of strong resistance force and can thus can be mistakenly recognized as *Strong Resistance*. Recognizing *Strong Resistance* also depends on how strong a user turns the seat. If the user turns the seat strongly, the resistive force may feel weak. This is why *Strong Resistance* was also confused with *Natural Resistance*.

Tilt. The average accuracy across all the conditions for tilt was 87.3%, lower than rotation and rolling. We found no significant effect of Force Profile ($p = 0.15$) but there was a significant effect of Cognitive Task ($F_{1,11} = 5.19, p < 0.05$). The recognition accuracy was lower with *Cognitive Load*

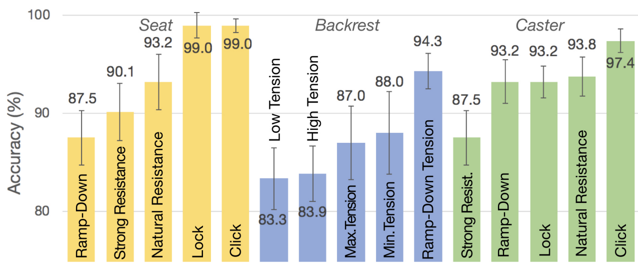


Figure 8: Accuracy of all force profiles. (Error bars show 95% *CI* in all figures)

(85%, *SD* = 16%) than with *No Load* (89%, *SD* = 12%), indicating that divided attention affected the recognizability of the force profiles for tilt. *Minimum*, *Maximum*, and *Ramp-Down Tension* had accuracies all above 90% when with *No Load*. The confusion matrix (Figure 9) shows that distinguishing between the two adjacent levels of spring tension (e.g., *Minimum* vs. *Low* or *Low* vs. *High Tension*) was more challenging for our participants, suggesting that people are in general less sensitive to the change in spring tension.

Rolling. The average accuracy across all the conditions for rolling was 93.0%, suggesting that the force profiles were relatively easy to recognize. Similar to rotation, we found a significant effect of Force Profile ($F_{3.01,33.91} = 3.74, p < 0.05$) but no effect of Cognitive Task ($p = 0.39$). *Click* (97.4%, *SD* = 6.4%) received the highest accuracy while *Strong Resistance* (87.5%, *SD* = 12.7%) received the lowest. Post-hoc pairwise comparison showed that the only significant difference was between *Click* and *Strong Resistance*. The confusion matrix (Figure 9) shows that *Strong Resistance* and *Ramp-Down* were confused with many other profiles. This is similar to rotation and we believe that the reason was the same.

Response Time

Average response time across all the conditions for rotation, tilt, and rolling was 4.25s, 6s, and 3.74s, respectively.

Rotation. There was a significant effect of Force Profile ($F_{2.29,25.19} = 5.12, p < 0.05$) and Cognitive Task ($F_{1,11} = 7.31, p < 0.05$). *Click* (3.64s, *SD* = 0.2s) was the quickest to recognize while *Strong Resistance* (4.91s, *SD* = 0.35s) was the slowest. There was a significant difference between *Strong Resistance* and *Click* while no significance was found between other pairs. *Click* was faster due to the distinguishable haptic landmark, which does not exist in any other force profiles. Interestingly, response time was significantly faster with *Cognitive Load* (4.65s) than *No Load* (3.85s). Although this sounds counterintuitive, participants reported that they felt the faster they performed the task, the fewer number of colors they had to count. This is in fact an encouraging

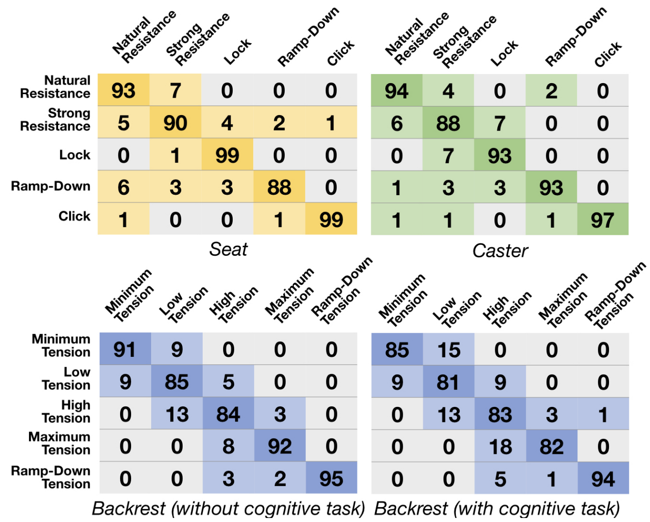


Figure 9: The confusion matrices of the Profile Recognition Accuracy (%).

result as it reveals that their initial reaction also led to higher accuracy.

Tilt. There was a significant effect for Force Profile ($F_{2.47,27.19} = 15.21, p < 0.01$) but no significant effect for Cognitive Task ($p = .19$). Post-hoc analysis showed that Minimum Tension was the fastest (4.6s, *SD* = 1.3s) amongst all force profiles (all $p < 0.01$). This is likely because participants could tilt the backrest quickly with less effort, and thus could react faster.

Rolling. There was a significant effect of Force Profile ($F_{2.50,27.57} = 8.44, p < 0.01$). *Natural Resistance* (3.14s, *SD* = 0.86s) was the quickest to recognize while *Lock* (4.23s, *SD* = 1.58) was the slowest. This is also likely because the less effort participants had to make to move the chair, the quicker they could react. Post-hoc analysis found the only significant difference was between *Lock* and *Natural Resistance*. There was a significant effect of Cognitive Task ($F_{1,11} = 13.05, p < 0.05$). Similar to rotation, response time was significantly faster with *Cognitive Load* (3.36s) than *No Load* (4.12s). We believe the reason was also the same.

Number of Attempts and Subjective Ratings

On average, participants took 1.05, 1.06, and 1.05 attempts to correctly identify the force profiles designed for rotation, tilt, and rolling. There was no significant effect of Cognitive Task and Force Profile for the three types of interactions (all $p > 0.05$). Participants informed us that when they chose to repeat, they wanted to double check their answer.

Subjective ratings were analyzed using repeated-measures ANOVA. The results showed a significant effect for Force

Profile for all the three interactions (all $p < 0.05$). Participants' ratings were all consistent with the quantitative result in recognition accuracy.

Discussion

Overall, our findings suggested that most of the force profiles are relatively easy to recognize. This is particularly true for rotation and rolling, whose recognition accuracies were not affected by a cognitive task, which was found difficult enough to negatively impact the recognizability of force profiles on a smart ring [18]. However, we did observe a trend that recognition accuracy decreased with the increase of cognitive load, which can eventually become significant after a certain threshold. *Strong Resistance* and *Ramp-Down* were the most confusing profiles for rotation and rolling, so we suggest avoiding them to convey critical information. In general, different profiles are suitable for different applications. For example, Click and Lock are appropriate to indicate urgent messages as they can be recognized reliably and quickly using rotation and rolling. All profiles are suitable for application scenarios involving entertainment (e.g. gaming) or providing haptic guidance for user's input (see the next section). This is also true for tilt, despite the force profiles designed for it being harder to recognize, especially with extra cognitive load. Our study showed that the number of tilt tension levels should be kept low, where anything between the minimum and maximum tension may increase confusion.

We did not ask participants to restrict their motion as minimally as possible, so they tended to move longer than needed to feel the force profiles. So, the current movement distances for rotation (47.3°), tilt (20.9°), and rolling (50.9 cm) represents an estimation of the upperbound of the scale of the motion of the three types of interactions.

Interactive chairs are expected to be used while a user is performing another task. It was thus important to ensure that interacting with the chair with the passive kinesthetic haptic output would not affect the performance of the user's other task. Our study showed that the average accuracy of the cognitive task was 96.5%, 95.4%, and 96% for rotation, tilt, and rolling, suggesting that the proposed haptic force output may not significantly impact the performance of a parallel task. The study also suggested that recognition accuracy was not affected by users' response speed. While this conclusion was drawn from the data of the last attempt, it is acceptable since most trials involved one attempt. More research is needed to determine how these results transfer to other scenarios. Finally, average response time for the three types of chair interactions (4.25s, 6s, and 3.74s) are acceptable for their applications considering the relatively large physical motions needed to interact with the chair.

9 DEMO APPLICATIONS

We implemented several applications to demonstrate the capabilities of Aarnio. Each application was designed through a participatory design workshop with people with varying backgrounds and physical capabilities. We brainstormed with our participants about their needs and limitation of the current office chair and how Aarnio can help.

On-demand Information Acquisition

Smartphone notifications are event driven and can be inadequate in social situations where there is a desire for a user to query information (e.g., finding how much time is left until the next meeting). The existing research allowed the user to query information by squeezing a smartphone [15] or rotating a smart ring [18]. Aarnio provides an alternative for a user to query information by rotating, tilting, or rolling the chair. In our implementation, the amount of resistive force for rotation indicates the time remaining until one's next meeting. For example, no force indicates plenty of time, a strong resistive force indicates 15 minutes to the meeting, and the seat becoming unmovable indicates that one is late to the meeting. A significant benefit of such interaction is in social settings, where repeatedly checking the time on one's smartphone can be considered inappropriate. *Rotating* or *tilting* the chair in a seated position does not reveal the user's interaction with a calendar because the motion is ambiguous about whether the user is using technology or just moving the chair. Thus, it can be a good alternative to check a smartphone.

Figure 10: Aarnio allows a user to (a) enter calorie information; (b) adjust a guitar rig without interrupting the tasks at hand.

Hands-free Interactions

Interacting with a smartphone often requires two hands. However, this can be challenging in situations where a user's hands are occupied by a task. For example, many fitness apps require a user to enter calorie information about a meal. A user may feel reluctant about doing while eating as their phone may get dirty. With our implementation (Figure 10a), the user can *rotate* the seat in some degrees to enter calorie ranges (e.g., 50 Cal per 5°). *Click* is provided to separate the targets to prevent the user from slipping off a desired range. This type of interaction can also be used in other hands-busy situations, such as playing a music instrument (e.g., guitar), where the user can *rotate* or *recline* the chair to adjust parameter values in the guitar rig without interrupting playing to operate the keyboard or mouse. We used *Ramp-Down* to roughly show parameter values (Figure 10b).

Gaming

Haptic feedback from the chair makes the gaming experience even more immersive. With our implementation of a VR first-person action game, the player steers a jeep by rotating the seat. If the front wheels are damaged, the seat is made hard to rotate or completely locked in place to restrict the mobility of the vehicle (Figure 11a). Additionally, increasing the spring tension of the backrest pushes the user's back to simulate the feeling of the player being pushed into the seat during car acceleration (Figure 11b). In an office chair racing game, the player feels bumpy (or *Clicks*) when comes across a "rocky road," and experiences *Ramp-Down* for gaining points (Figure 12a).

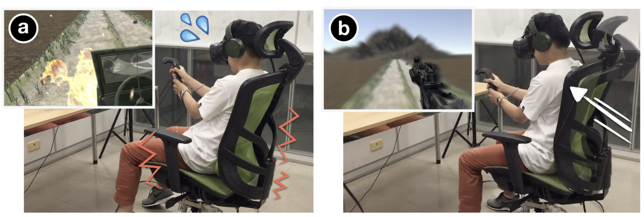


Figure 11: Aarnio simulates the (a) damage or (b) acceleration of a vehicle in a VR game.

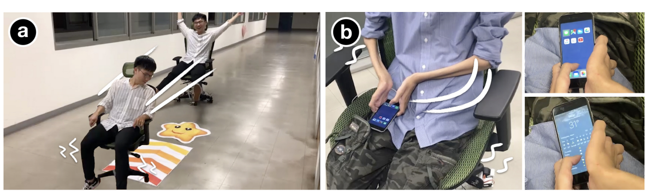


Figure 12: (a) Aarnio simulates game element in chair racing game. (b) A motor impaired user holds the phone using both hands and navigates the screen using the chair.

Interaction Techniques for People with Disabilities

Interacting with a desktop or smartphone is still challenging for people with motor or visual impairments, especially for tasks requiring fine-grained motor control. Quick and frequent tasks like those mentioned previously (e.g., quickly checking a calendar or enter calories), takes a significant amount of time and effort to complete. From our interview with a user with hand impairment, we see people with disabilities can also benefit from Aarnio in these tasks by acquiring information via the force output or performing input with the assistance of a guiding force (Figure 12b). In our implementation, people with hand and motor impairments can rotate the chair to quickly switch between desired commands or applications. We used *Click* between two adjacent targets to guide a user through navigating the menu items. Selection can be made using dwell. Our system also allows those with visually impairments to recline backward to query the time remaining until the next bus.

10 LIMITATIONS & FUTURE WORK

We discuss insights gained, propose future research, and acknowledge the limitations of our work.

Implementation. The current implementation was sufficient to evaluate our proposed force profiles for foreground interactions. However, it could be iterated upon to integrate wiring, sensors, computers, and haptic systems into a self-contained chair. There are also spaces for the haptic system to be improved to enable new capabilities. For example, a faster and stronger motor can be used for the tension controller to increase the response time to enable new force profiles on the backrest (e.g., Click). As the mechanical joints for rotation, tilting and rolling are similar for most swivel chairs, another interesting direction for future research is to develop the haptic systems into self-contained modules that can be attached to the joints of any office chair.

Interactions. The interactions that we implemented should be considered exploratory in nature. They represent a small sample of what is possible with Aarnio, whose concept can be extended to other interactive furniture and smart home appliances. In terms of interaction design, though we received no negative feedback, it is important to take the user's comfort, ergonomics, and safety into consideration. Calibration for individual users may provide the best experience. The original functions of a chair should not be sacrificed. The user should have full control over the haptic system so that force output can be completely dismissed, if needed. Safety is also an important consideration in the design of Aarnio's interactions. For example, the backrest should not be too soft if the user expects it to be firm to lean against. It can be dangerous otherwise.

Force profiles and evaluation. Our work focused on simple force profiles and their distinguishability, to demonstrate the promise of passive kinesthetic force output for foreground interactions on an interactive chair. The study result may not be generalizable to other types of chairs or floors. We also realized the importance of accessing the perceivability of the force profiles to understand the minimal amount, and the varying levels of force output that a user can perceive. Our study on the four levels of spring tension touched upon this interesting area of experimentation to explore. We expect that the outcomes of such studies can provide more insight for the design of its numerous applications.

11 CONCLUSION

In this paper, we propose passive kinesthetic force output for foreground interactions on an interactive chair. Our haptic technique modulates the natural resistive force of rotating, tilting, and rolling an office chair to restrict a user's motion to support new applications in a ubiquitous computing environment. We demonstrated our idea through a proof-of-concept prototype, where we augmented the shaft of the seat, the spring of the backrest, and caster wheels using carefully designed braking or spring tension controlling systems. For each type of interaction, we designed five force profiles and tested their recognizability via three controlled user studies. Our results suggested that participants could distinguish between the force profiles with accuracies of 93.75% (rotation), 87.3% (tilt), and 93.0% (rolling). Finally, we demonstrated several applications that can be enabled by this new haptic output. We believe that our work can inspire many new researches in interactive furniture and smart IoT.

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