TiltChair: Manipulative Posture Guidance by Actively Inclining the Seat of an Office Chair

Kazuyuki Fujita*
k-fujita@riec.tohoku.ac.jp
Tohoku University, Japan

Aoi Suzuki*
aoi1932@riec.tohoku.ac.jp
Tohoku University, Japan

Kazuki Takashima
takashima@riec.tohoku.ac.jp
Tohoku University, Japan

Kaori Ikematsu
k-ikematsu@acm.org
Yahoo Japan Corporation
Tohoku University, Japan

Yoshifumi Kitamura
kitamura@riec.tohoku.ac.jp
Tohoku University, Japan

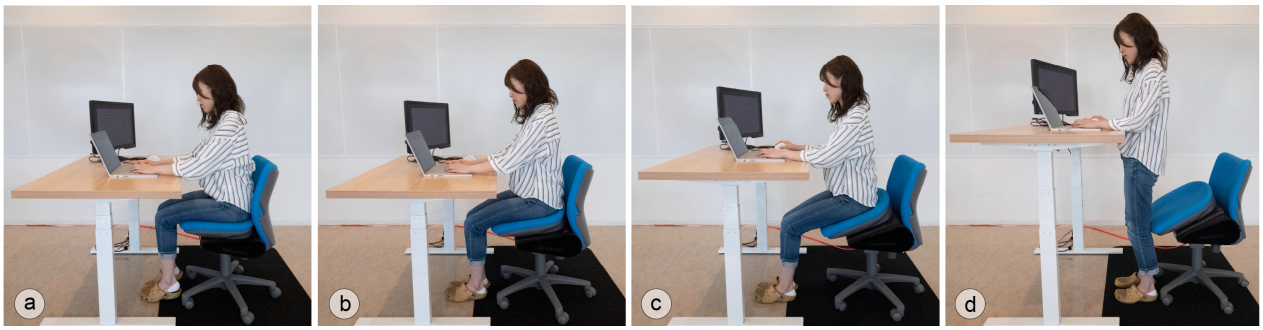


Figure 1: TiltChair promotes posture change by actively inclining the seat, e.g., when it detects the user's prolonged sitting. To achieve manipulative but unobtrusive posture guidance, this study investigates how the seating angle and the inclining motions affect the user experience. The seating angles in the figures are (a) 0 deg, (b) 15 deg, (c) 35 deg, and (d) 40 deg.

ABSTRACT

We propose TiltChair, an actuated office chair that physically manipulates the user's posture by actively inclining the chair's seat to address problems associated with prolonged sitting. The system controls the inclination angle and motion speed with the aim of achieving manipulative but unobtrusive posture guidance. To demonstrate its potential, we first built a prototype of TiltChair with a seat that could be tilted by pneumatic control. We then investigated the effects of the seat's inclination angle and motions on task performance and overall sitting experience through two experiments. The results show that the inclination angle mainly affects the difficulty of maintaining one's posture, while the motion speed affected the conspicuousness and subjective acceptability of the motion. However, these seating conditions did not affect objective task performance. Based on these results, we propose a design space for facilitating effective seat-inclination behavior using the three dimensions of angle, speed, and continuity. Furthermore, we discuss promising applications.

CCS CONCEPTS

• **Human-centered computing** → **Empirical studies in interaction design**; • **Computer systems organization** → *Sensors and actuators.*

KEYWORDS

posture change, actuated furniture, well-being, adaptive workplaces

ACM Reference Format:
Kazuyuki Fujita, Aoi Suzuki, Kazuki Takashima, Kaori Ikematsu, and Yoshifumi Kitamura. 2021. TiltChair: Manipulative Posture Guidance by Actively Inclining the Seat of an Office Chair. In *CHI Conference on Human Factors in Computing Systems (CHI '21), May 8–13, 2021, Yokohama, Japan.* ACM, New York, NY, USA, 14 pages. https://doi.org/10.1145/3411764.3445151

*Both authors contributed equally to the paper.

CHI '21, May 8–13, 2021, Yokohama, Japan

ACM ISBN 978-1-4503-8096-6/21/05…$15.00
https://doi.org/10.1145/3411764.3445151

1 INTRODUCTION

A large number of people spend a considerable part of their days sitting at their desks. Prolonged and static sitting is problematic because it can cause musculoskeletal discomfort [23, 25] as well as increased all-cause mortality [15] or risk of various diseases [5, 9, 15, 59]. One common approach to this in ergonomics and physiology is to improve or replace office chairs, since their seat and/or backrest passively moves in response to the user's movements [18, 39, 43, 61]. However, some studies have pointed out there is little quantitative evidence to support the effect of this approach [39, 43]. At the same time, height-adjustable (sit-stand) desks and other exercise-integrated workstations have been developed [12, 34, 38, 51, 53], but these are limited by the need for the user's conscious participation [14, 17].

In the field of human-computer interaction (HCI), many studies have been conducted on monitoring and correcting posture. Posture correction has been achieved in various ways, such as on-screen notification [1, 24, 27], vibrotactile feedback [24, 69], and shape-changing desktop objects [13, 24, 28]. The problem with these methods, however, is that they still rely on the user's intentionality; furthermore, the more noticeable methods are also more likely to be interruptive to users [24]. Another approach is to slowly move a monitor or virtual screen at an imperceptible speed, in order to unobtrusively manipulate the user's posture by guiding their eye movements [49, 50]. These techniques are sophisticated and have inspired us, but their effective range is limited to tasks where the user is looking at a screen.

Here, we focus instead on the approach of controlling the inclination of the chair's seat, which can have a direct effect on the seating posture regardless of the working context. We believe that the chair's inclination would create a transient state between standing and sitting (referred to as *half-sitting posture* [63]), thus facilitating a natural transition of the user's posture. Some prior work has already introduced chairs that can passively tilt the seat [6–8, 36, 63], and in practice, some electric riser chairs (mainly for elderly people) have an inclination mechanism. However, no study have yet examined active inclination in the context of addressing prolonged sitting or investigated the effect of seat inclination on workability and task interruption.

Therefore, in this study we propose TiltChair, an actuated office chair that promotes posture change by actively inclining the seat. Figure 1 shows a usage image of TiltChair when used with a sit-stand desk. Unlike prior works that rely on user intentionality, TiltChair can *manipulatively* change the user's posture by physically guiding him/her to a standing or half-sitting posture. At the same time, changing the inclination angle and/or controlling the motion offers the potential to influence the user experience, such as by adjusting the extent of posture change or minimizing task interruption. These benefits could cover a wide range of applications. To demonstrate the system's potential, this paper explores how seat inclination affects the user experience. First, we implement a mechanism to dynamically incline the seat angle of an office chair using pneumatic control. We then experimentally examine the effects of the inclination angle (in the first experiment) and its motions (in the second experiment) on the user's task performance, subjective acceptability, and postural behavior. Based on the results, we introduce a design space for implementing the seat-inclination behavior in several promising applications with TiltChair. Finally, we report an initial usability test (the third experiment) when TiltChair is used for addressing the problems of prolonged sitting. The contributions of this paper are as follows.

- Proposing and implementing TiltChair, an actuated office chair that facilitates posture change by dynamically inclining the chair's seat,
- Understanding how the seat's inclination angle and its primitive motions affect the user's task performance, subjective acceptability, and postural behavior through two user studies,
- Introducing a design space for implementing seat inclination based on the experimental results and exploring corresponding application examples, and
- Reporting the initial user feedback in a practical use case.

2 BACKGROUND AND RELATED WORK

2.1 Ergonomic Chairs and Desks

Only recently have we obtained reliable evidence on the long-term adverse health outcomes caused by prolonged sitting. A study of approximately 8,000 participants [15] revealed that both total sedentary time and uninterrupted sitting duration were associated with all-cause mortality. To reduce such risks, it has been proven effective to break up sitting time with standing or physical activities [5].

In the fields of ergonomics and physiology, researchers have so far explored *dynamic* sitting that encourages users to make frequent posture changes while seated [43, 61], mainly to alleviate musculoskeletal discomfort such as low back pain [23, 25]. Some works have attempted to develop improved office chairs [30], stability balls [18, 39], and dynamic stimulus of the seat's rotation in the horizontal plane [60]. Similarly, office chairs that can passively tilt the seat in accordance with the user's movement have been introduced, mainly to facilitate trunk movements due to unstable seat fixation [6–8]. However, the effectiveness of these dynamic sitting approaches has been shown to be lacking in quantitative evidence; rather, several studies have even suggested they have no positive effect on muscle activation [39] or lower back pain [43]. Furthermore, these efforts have not focused on the problems of breaking up prolonged sitting, as explained above.

Regarding desks, there have also been many attempts to enable users to stand up and/or exercise. Not surprisingly, several reports indicate that sit-stand desks significantly reduce sitting time compared to conventional sit desks [51, 59, 65]. Other types of desks, such as treadmill desks [34, 53] and pedal desks [12, 38], have also been considered. However, their benefits would not be uniformly available to all users because such office furniture requires conscious participation [14, 17].

2.2 Interactive Furniture

An increasing amount of research has been conducted in recent years on interactive furniture from a variety of perspectives, including health, comfort, productivity, and privacy in the working environment. One mainstream approach is to support collaboration by variously transforming the tabletop shape and/or its angle [19, 20, 31, 55, 56, 62]. As an approach to enriching the personal working environment, Mediated Atmospheres [68] tried to visually and auditorily create a comfortable atmosphere in the environment. ActiveErgo [66] is a robotic furniture system that can automatically adjust the desk, chair, and monitor's position based on the sensed user's skeletal information. Body2Desk [32] is a virtual reality (VR) simulator for designing desk environments with assistance from the perspective of ergonomics. There have also been attempts to modularize physical props to allow users to build their own workspaces [45, 54]. These systems enable us to provide a workspace that fits the user's needs, and some of them involve ergonomics, but they do not specifically target ways to promote postural change.

2.3 Monitoring/Correcting Posture

In HCI, various methods have been explored to monitor the seating posture, such as methods using a camera [26, 27, 66], pressure sensors on the seat and backrest [41], 9-DoF sensors attached to a 3D printed object [16], and garment-like wearable sensors [37, 64]. At the same time, other studies notify users of their inappropriate seating postures or prolonged sitting to facilitate posture change. This has been achieved by a variety of methods, including on-screen visualization [1, 27], vibrotactile feedback [69], and an implicit method using shape-changing agents on the desk [13, 28]. Haller et al. [24] compared these three different types of interruption feedback, and the results showed that vibrotactile feedback was easily noticed but perceived as highly annoying by the participants, while the desktop agent tended to be ignored. These studies demonstrated that promoting posture change while also balancing noticeability with unobtrusiveness is quite difficult.

Recent studies have explored ways of more direct posture guidance than interruptive notifications. Kiyokawa et al. proposed a robotic chair that can stimulate the user by generating a horse-riding motion on the seat according to the user's drowsiness or concentration level [29]. Gust et al. also proposed a method to stimulate the user to change his/her posture by applying pressure to the seat or changing its height [21]. These studies are based on concepts similar to ours, but they do not focus on actively manipulating posture change; in addition, they conducted no detailed user studies to investigate the effect of interruptions during a task. Lee et al. explored the timing for automatically changing the height of a sit-stand desk with minimal discomfort or interruption for the user [33]. They found the best timing was in-between tasks, while their experiment showed that actuation during a task interfered with the task due to the movement.

Alternatively, another method was proposed to guide the user's posture by dynamically controlling the position and orientation of the monitor watched by the user [2, 11, 49, 50]. In particular, Shin et al. proposed a method of unobtrusively guiding the user to a correct posture by slowly moving the monitor below the user's perception threshold [50], and their later work applied a similar idea to a VR environment [49]. However, these methods require the user to continue looking at the screen, so they cannot be used for some tasks, e.g., while handcrafting items or using handheld devices. Therefore, we focus on seat inclination as a possible way to manipulatively but unobtrusively change posture, without its application being limited to a few tasks.

3 TILTCHAIR

Here, we propose TiltChair, an actuated office chair that physically acts on the user to promote posture change by actively tilting the chair's seat. Our core idea is that controlling the seat's inclination could purposefully adjust the manipulation force and obtrusiveness, which could be leveraged to break up prolonged periods of sitting in a wide range of posture guidance contexts, e.g., from a subtle guidance that weakly motivates minor posture changes to a physically intrusive guidance that forces the user to stand up. The rest of this section briefly describes the system design and actual implementation of its prototype.

3.1 System Design

We implemented a proof-of-concept prototype of TiltChair under the following requirements.

The system is an add-on to the seat of a normal office chair. This is to preserve the fundamental sitting experience that ordinary office chairs provide.

The system controls the inclination angle and its speed. Since we assume that these variables mainly affect the user experience of posture change, they should be arbitrarily controllable. In addition, since our interest lies in changing the seating angle, the seat motion should be independent of the backrest.

The seat inclines to bring the user to a half-sitting posture. While various possible form factors can be used in designing the seat actuation, we adopted one that brings the user to a half-sitting posture. Specifically, the seat surface transitions between a horizontal state and a forward tilting state (backward tilting not permitted) with the front edge of the seat as the axis of rotation. This manner of inclination is expected to raise the user's hip position according to the tilting angle, thus achieving a natural transition between sitting and standing.

The inclining motion is smooth enough to avoid any discomfort to the user. A sudden acceleration or deceleration during the inclining motion might impose mental or physical stress on the user. In addition, motions other than the inclining motion (e.g., vibrations from the motor) should clearly be avoided. For these reasons, the system needs to carefully ensure smooth movement regardless of the inclination angle and speed.

Considering these requirements, we adopted a method to control the seating angle using pneumatic control of an inflatable component beneath the seat's surface. Several studies have previously employed pneumatic shape-changing interfaces that humans can lean on [47, 54, 58], and we believe that this approach would be the easiest way to meet our requirements due to its air elasticity, weight capacity, and shape-shifting capability.

3.2 Implementation

3.2.1 Inclination mechanism. Seat inclination is achieved by inserting a pneumatic control mechanism (hereafter, inclination mechanism) beneath the seat surface of an ordinary office chair (BIT-X45LO-F-BL, IRISCHITOSE). Figure 2a shows a system overview of TiltChair, and Figure 2b shows the inclination mechanism. The inclination mechanism consists of two wooden plates (W300×D300×H20 mm) connected by two hinges (B-214-4, TAKIGEN) and an inflatable bag (Toughage Triangle Inflatable Pillow, W450×D360×160 mm when fully inflated, 120 kg load capacity) inserted between the plates. The upper plate is fixed to the bottom of the seat, and the lower plate is attached to the seat pan. We used several 3D-printed parts to attach the plates to the seat and to set the seating angle to 0 deg without inflation. The inflatable bag is connected to an air compressor (ACP-10A, EARTH MAN) and a vacuum pump (TA150XD,

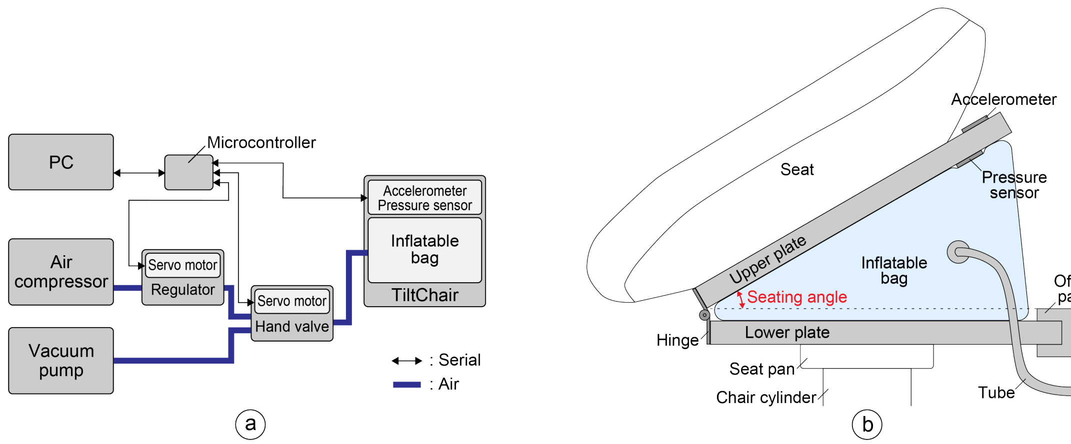


Figure 2: (a) System configuration of TiltChair; (b) side view of the inclination mechanism (the backrest is omitted). The seating angle is defined as the angle of the upper plate from a horizontal plane.

TASCO) through a hand valve (250V, KOGANEI), and inflation and deflation can be switched by controlling the hand valve with a servo motor (DS3218mg, Goolsky). The air inflow is controlled by rotating a dial on the regulator (AT-77, Fujiwara Sangyo) with another equivalent servo motor. The upper plate is equipped with an accelerometer (MPU6050, IvenSense) to measure the inclination angle and a pressure sensor (BME280, Bosch Sensortec) to obtain the user's sitting state (but the latter is not used in the two subsequent user studies). For the microcontroller, Arduino Uno (Gravitech) is used.

The seat angle can be raised up to 55 deg with this mechanism. The seat height with the inclination mechanism is 9.0 cm higher than the original chair, which is adjustable between 92 and 102 cm. We considered offsetting this increase, but we did not because prior work [7] reported that a tiltable seat is more acceptable to users with a slightly higher seat, and also because our preliminary test (N=5) received no negative response to the seat height.

3.2.2 Controlling Algorithm. The speed of the inclining motion is controlled by changing the inflation rate, which is adjusted by rotating the regulator's dial with the servo motor. To achieve this, we examined the relationship between the dial's rotation angle and the resulting inclination speed of the seat. We measured the inclination speed when a user (72 kg weight) was seated on TiltChair while increasing the dial's rotation angle at intervals of 1 deg between 0 and 40 deg. The speed was calculated by the time taken to increase the seat angle from 0 to 30 deg. As a result, the relationship between the dial's rotation angle x (deg) and the obtained inclination speed of the seat y (deg/min) was fitted to a logistic curve $y = a/(1+be^{cx})$ and found to be $a = 1.02 \times 10^2$, $b = 1.30 \times 10^3$, and $c = -0.270$, with residual standard error of 2.25 deg/min and 38 degrees of freedom. The result means that the dial rotation angle x, which gives a certain seat speed y, can be determined by its inverse function. Although the user's weight and body movement might cause slight fluctuations in the seating angle, we did not employ feedback control as the speed control because these effects appeared to be negligible.

We performed a test to measure the accuracy of the inclining motion. We operated the seat motion at two different speeds (5 deg/min and 40 deg/min) from 0 deg to 35 deg with different users (N=5) seated. The time series data of the seating angle calculated from the accelerometer was acquired at 4 Hz, and the error of the measured angle from the ideal value was measured when the ideal motion was defined as reaching 35 deg at a constant speed from 0 deg. Measurement of a total of 9450 acquired samples showed that the mean absolute error was 1.55 ± 0.534 deg (mean error rate was 4.42 %). This was small enough to be used in the following experiments.

4 USER STUDY

This section reports experiments conducted to investigate how the change in seating angle using TiltChair affects the user experience. We first conducted a user study (Experiment 1: E1) to investigate the effects of the static seating angle on the user's sense of workability and subjective acceptability. We then carried out another user study (Experiment 2: E2) to investigate the effects of the inclining motions on the user's postural behavior during the task as well as workability and subjective acceptability. Another user test (Experiment 3: E3) on a TiltChair application will be described later in Section 6. The study designs of these experiments were officially approved by our university's ethics committee.

4.1 E1: Investigation of Static Inclination

4.1.1 E1 design. The experiment was a one-factor within-subjects design, where participants were required to perform a desk-work task under different static seating angles. Our preliminary study (N=5) on seating angle found that four of the users were unable to maintain a sitting posture when the angle was 40 deg, so the seating angle tested in this experiment was set within the range of 0 to 40 deg at 5-deg intervals.

We adopted a text-typing task as typical desk-related work, which has been frequently used in prior work (e.g., [4, 8, 33, 61]). We decided to set the duration of each trial to three minutes with a single repetition, mainly because we were concerned about the drop in concentration resulting from an experiment with an excessively long duration. We acknowledged that this duration would be too short to examine prolonged effects like fatigue, but we decided it

Figure 3: Experimental setup for E1 and E2.

would be long enough to investigate whether there was any obvious discomfort or decrease in task performance.

The measurements adopted metrics for task performance and sitting experience. For the metrics of task performance, we examined text-input speed, error rate, and subjective workload. The text-input speed was calculated by the number of words typed per minute. The error rate was defined as the Levenshtein distance [67] between the input text and the reference text divided by the total number of characters typed. For the subjective load, we employed a modified NASA-TLX survey, where the *physical demand* subscale was replaced with *distraction* (based on [33, 46]), which was done to clearly separate the workload of the text-input task from the sitting experience. For the metrics of the sitting experience, we used a seven-point Likert scale with an original item on seating difficulty in maintaining posture during the trial (where 7 was "difficult" and 1 was "not difficult"), as well as a two-alternative forced-choice question on overall acceptability ("acceptable" or "unacceptable") of the sitting experience. In addition, participants commented on their perceptions and impressions of each seating condition.

4.1.2 E1 Apparatus. Figure 3 shows the experimental environment. The participants sat on the TiltChair in front of an electric sit-stand desk (AIM02E003, AIMEZO), whose height was adjustable from 66 to 131 cm. A cloth floor mat was placed under the chair to prevent the chair from sliding too much. A laptop PC (Microsoft Surface Book2, 15-inch screen) was used by participants for their tasks. The participants wore wireless noise-canceling headphones (SONY WH-H900N) to listen to ambient sound because the air compressor connected to TiltChair sometimes generated noise. We installed a video camera next to the participants to record them, to which they gave their consent.

The experiment was conducted in accordance with the guidelines of COVID-19 infection prevention issued by our institution. Specifically, we confirmed before the experiment that the experimenter and each participant were healthy and had no contact with any infected person within the last two weeks. They wore a mask throughout the experiment. In the room, splash prevention sheets were installed between them. All of the equipment and furniture were disinfected with rubbing alcohol before and after the experiment, and the room was continuously ventilated during the experiment.

4.1.3 E1 Participants. Twelve undergraduate or graduate students (eight males and four females, mean age: 21.3 (SD=6.78)) participated in the experiment. All participants had no prior knowledge of this study. Their mean height was 166.9 cm (SD=9.691). According to their self-declaration, they routinely sat in their chairs for 7.17 hours (SD=2.79) a day. We paid them an honorarium (approx. 30 USD per participant) in accordance with university regulations.

4.1.4 E1 Procedure. The participants were seated in an ordinary chair, received an explanation of the experiment, and signed a consent form. They then started the practice session. The task was to input as much text as possible within three minutes according to the reference text displayed on the laptop screen. The text was derived from Aesop's Fables, and the input form was created with Google Forms. After the practice session, the participants were asked to sit on TiltChair (at a specific seating angle) and to adjust the height of the chair and desk to a comfortable state for them. After that, they were asked to wear the headphones, and they started the trial at the experimenter's cue. After each trial, the participants moved back to the ordinary chair and completed a questionnaire on the trial, while the experimenter prepared the seating angle for the next trial. The seating angles were presented in random order and remained constant during each trial. The trials were done nine times, and their order was counterbalanced among the participants. The participants were in advance instructed that they could stand up or change the desk height at any time, even during a trial. At the end of all trials, they were asked to give their overall impressions and comments. The experiment's total duration was about 70 minutes per participant.

4.1.5 E1 Results. A total of 108 trials were conducted without any problem. At 40 deg, four participants could not execute the task because they could not maintain a sitting posture. In these trials, they did not answer the NASA-TLX survey but did answer our questionnaire on sitting experience (missing data were supplemented by substituting the mean for each participant in ANOVA). As our analysis protocol, we conducted a normality test (Shapiro-Wilk test) and a test of equality of variance (Levene's test) for each item of obtained data, and then we performed parametric analyses only if none of the test results was significant ($p > .05$), and non-parametric analyses otherwise. We identify the participants as P1-P12 below.

Task performance. Figure 4 and Figure 5 show the results of text input speed and error rate, respectively, in relation to seating angle. The error bars show the standard error. A repeated measures one-way ANOVA for text input speed revealed no main effect on seating angle ($F(8, 88) = 0.509, p = .847$). Furthermore, an equivalent analysis for the error rate showed no main effect on seating angle ($F(8, 88) = 1.07, p = .394$).

Figure 6 shows the scores of Raw-TLX (RTLX), i.e., the mean score of all subscales of the modified NASA-TLX questionnaire. A repeated measures one-way ANOVA for RTLX showed a main effect on seating angle ($F(8, 88) = 4.24, p < .001$). Bonferroni's multiple comparison revealed significant differences (see Figure 6).

Sitting experience. Figure 7 shows a boxplot of obtained subjective difficulty in keeping posture related to seating angle. A Friedman test showed that the seating angle had a significant effect on the score ($\chi^2(8) = 54.7, p < .001$). Scheffe's multiple comparisons revealed significant differences (see Figure 7). Figure 8 shows

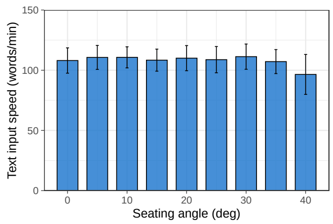


Figure 4: Results of text-input speed in E1 (excluding missing data items at 40 deg).

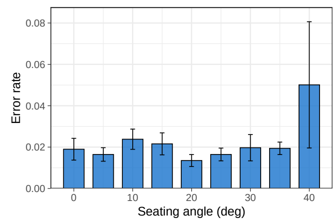


Figure 5: Results of error rate in E1 (excluding missing data items at 40 deg).

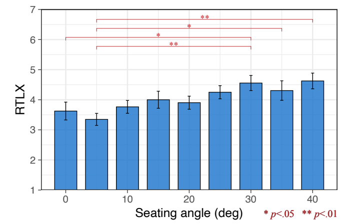


Figure 6: Results of RTLX scores in E1 (excluding missing data items at 40 deg).

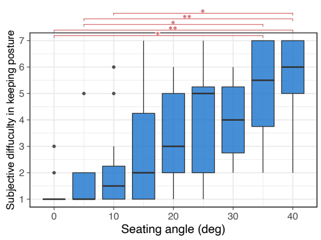


Figure 7: Results for subjective difficulty in keeping posture in E1.

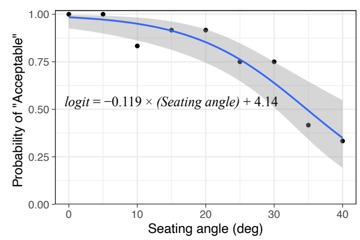


Figure 8: Probability that participants answered the seating angle was acceptable in E1.

the results of the two alternatives for subjective acceptability of seating experience, which revealed that the probability of acceptance generally decreased with the seating angle. We obtained an approximation curve for acceptability through a binomial logistic regression analysis (Figure 8).

According to the participants' comments expressed after experiencing each angle, most of them stated that they did not feel any discomfort or did not pay attention to the inclination up to about 15 deg. Some even said they felt more comfortable than when there was no inclination (P2, P5, P8). At 25 deg, some complained of physical load (P1, P3, P6, P8, P10), and some stated they could not fully concentrate on their work due to their awareness of maintaining their posture (P3, P10). At 35 deg, most comments were clearly negative, with some commenting that they almost felt as if they were slipping off the chair (P1, P2, P6, P8), while others complained of physical fatigue (P1, P7), mental stress (P3), and mental pressure (P10). At 40 deg, many of them could not sit at all (P1, P6, P8, P9) or, even if they could, complained of difficulty in executing the task (P2, P3, P10, P12). By contrast, some stated that they did not feel so much strain even at 40 deg (P4, P7), and some were able to concentrate on the task from the latter part of the trial (P11, P12).

4.1.6 E1 Discussion. One major finding in this experiment was that the seating angle itself did not have a pronounced negative effect on the objective measures of text-input speed and error rate, unless the participants were physically unable to sit down. It was also found that the subjective workload increased when the seat was inclined at a larger angle. This might be due to the need for cognitive resources to maintain the user's posture, as mentioned by many participants. Taken together, these results can be interpreted as evidence that the user's additional physical/mental load caused by the seating angle was not substantial enough to reduce performance in the text-input task. The long-time effect of the seating angle is still not clear due to the short trial time, but in the interviews, many participants (P3, P7, P8, P9, P10, P12) mentioned negative aspects such as fatigue or a drop in task performance when asked about the prospects of sitting on an inclined seat much longer. This suggests that it would be better to avoid prolonged inclination; rather, it would be better to activate the inclination temporarily or intermittently.

The experimental results also clearly show that the participants' subjective difficulty in maintaining their posture increased as the seating angle increased. This might be an obvious result, but we interpret it as an important observation that demonstrates the potential of active manipulation of posture change according to the seating angle. Subjective comments also revealed that moderate angles (less than around 15 deg) had few negative effects, while steep angles (more than around 30 deg) seemed to clearly disrupt the sitting experience. At 40 deg, the participants were divided into those who could sit and those who could not. The reason for this division is attributed to their individual differences in anthropometric characteristics, as well as the material (friction coefficient) of their lower-body clothes.

When asked about the use of an inclining seat in actual desk work, interestingly, five participants (P1, P3, P4, P8, P11) commented that they could use it when they wanted to concentrate on their work. According to them, this was because the tilt pushed the body forward, which leads them to a posture similar to that of concentrating on the screen. Although this is the case only when the user is facing a screen, it raises implications for a new application area of seat inclination.

4.2 E2: Investigation of Dynamic Inclination

4.2.1 E2 design. The second experiment involved a desk-work task similar to E1 while several different patterns of inclining motions occurred on the seat. We employed a one-factor within-subjects design. The independent variable was seating condition determined by the combination of inclining motion speed (i.e., angular velocity of the seating angle) and arrival angle (i.e., the angle at which the motion ends), which were considered primitive parameters of the inclining motion. For the inclining motion speed, we set five speeds (5, 10, 20, 40, and 80 deg/min), which reflected the findings from our preliminary test (N=4), where participants were sensitive to noticing the motion even at quite low speeds but also considered much higher speeds acceptable. In order to simultaneously cover the requirements of these investigations without increasing the number of trials, we set up exponentially incremental speed conditions. For the arrival angle, we used the results of E1 as a guide, thus choosing two angles: 15 deg, at which we expected it to be easy to maintain one's posture, and 35 deg, at which it would be clearly difficult to maintain one's posture. Consequently, participants were presented with a total of eleven conditions, which consisted of a combination of the 5 motion speeds $\times$ 2 arrival angles plus a static condition with no motion. In addition, the timing to start the motion (t_0) from the beginning of the trial was randomly determined between 0 to 60 sec to prevent the participants from memorizing it. The resting trial time after the motion was adjusted accordingly (as $60 - t_0$ sec). Note that since this experiment primarily investigated the task *during* the inclining motion, the duration of the trials differed for varying conditions of motion speed and arrival angle: the longest condition (*35-deg arrival – 5-deg/min speed*) took eight minutes, and the shortest condition (*15-deg arrival – 80-deg/min speed*) took 71.25 sec per trial. The static seat condition lasted two minutes.

The measurements were divided into metrics of task performance and sitting experience. For the metrics of task performance, we obtained the text input speed, error rate, and NASA-TLX workload, as in E1. For the sitting experience metrics, we obtained subjective difficulty in maintaining posture and overall acceptability as in E1, and also observed participants' postural behavior by manually coding the captured video. In addition, we attempted to investigate the noticeability of the motion for the participants. Our preliminary test (N=4) showed that it was nearly impossible to be unaware of the motions through the trial (i.e., even if the motion were slow enough to be unnoticed, the accumulated displacement of the seat angle would definitely be perceivable). Therefore, we used the seating angle at which the participants noticed the motion as the noticeability measure.

4.2.2 E2 Participants. Twelve undergraduate or graduate students (eight males and four females, mean age: 21.3 (SD=6.78)) participated in E2. All of them had also participated in E1, but E2 was held on different days. As with E1, they received an honorarium (approx. 30 USD per participant) in accordance with university regulations.

4.2.3 E2 Procedure. The experimental setup was the same as that used in E1. Before the experiment, the participants were informed about the seat's inclining motion occurring during the task but were not told about the purpose of the motion (e.g., to reduce prolonged sitting) in order to avoid bias in their behavior. The overall procedure was roughly the same as in E1. The difference was that the participants were asked to verbally signal the experimenter as soon as they were definitely aware of the seating motion during the trial, while still continuing the text-input task. The combinations of motion speed and arrival angle conditions were presented in random order. The order of presentation was counterbalanced among the participants. As in E1, the participants were allowed to stand up or change desk height at any time. The entire duration of the experiment was about 75 minutes per participant.

4.2.4 E2 Results. A total of 121 trials were conducted without any problem. We performed the analysis using the same protocol as that in E1. The participants' identifications shown below are the same as those in E1.

Task performance. Figure 9 and Figure 10 show the results of the text-input speed and error rate, respectively, for each seating condition. One-way repeated measures ANOVA for text-input speed revealed no main effect of the seating condition (including 11 conditions) ($F(10, 110) = 0.571, p = .835$). A similar analysis for error rate also revealed no main effect of the seating condition ($F(10, 110) = 0.783, p = .645$).

Figure 11 shows the result of the RTLX scores for each seating condition. One-way repeated measures ANOVA for RTLX revealed a main effect of the seating condition ($F(10, 110) = 2.98, p < .01$). Bonferroni's multiple comparisons for the main effect showed significant differences (see Figure 11). Then, we focused on the data with motion (including 2 arrival angles $\times$ 5 motion speeds = 10 conditions) and conducted a two-way repeated measures ANOVA, which revealed that there was a main effect of arrival angle ($F(1, 11) = 11.2, p < .01$) but no main effect of motion speed ($F(4, 44) = 1.42, p = .232$).

Sitting experience. Figure 12 shows the boxplot of the obtained subjective difficulty in maintaining one's posture for each seating condition with motion. A Friedman test showed that the seating condition had a significant effect on the score ($\chi^2(1) = 46.3, p < .001$). Scheffe's multiple comparisons revealed significant differences (see Figure 12). We then conducted Friedman tests for each characteristic of the motion and found a significant difference for the arrival angle ($\chi^2(1) = 9.68, p < .01$), while no significant difference was found for the motion speed ($\chi^2(4) = 5.31, p = .257$).

From the video observation, we found that the frequency and quality of the behaviors differed mainly according to the arrival angle (Table 1 in Appendix shows a list of observed behaviors). At the 15-deg arrival angle, half or fewer of the participants showed certain kinds of postural behavior at any speed condition. The most frequently observed behaviors were mostly minor, such as moving the chair backwards, raising the upper body (including stretching the back), changing the legs' positions, and moving the laptop forward. At the 35-deg arrival angle, similar minor behaviors were also observed, but the number of participants and the frequency of the behaviors clearly increased. Furthermore, some participants performed major postural actions such as raising the desk height (P11 and P12 in most speed conditions at 35-deg arrival) and standing up (P6 and P8 in 40 deg/min and P6 in 80 deg/min speed condition at 35-deg arrival). In the interviews, all but one (P2) of the participants indicated that they wanted to change their posture in response to the seat motion. When asked when they wanted to change their posture, they answered they did so during any motion (P6), when the seating angle was steep (P1, P5, P7, P9, P10), and when the speed of the motion was fast (P8, P10). Two participants (P3, P4) answered they would have performed a major posture change if the task had lasted longer.

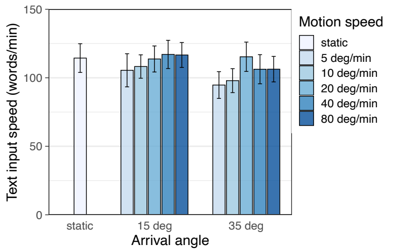


Figure 9: Results of text-input speed in E2.

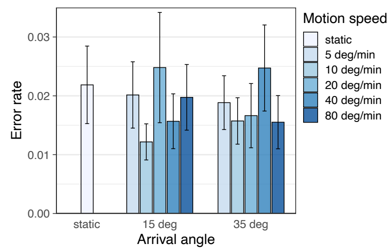


Figure 10: Results of error rate in E2.

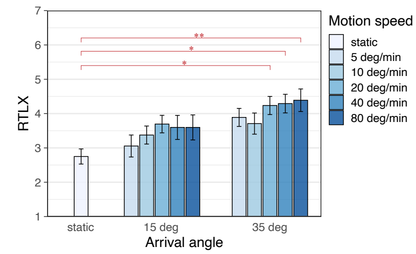


Figure 11: Results of RTLX in E2.

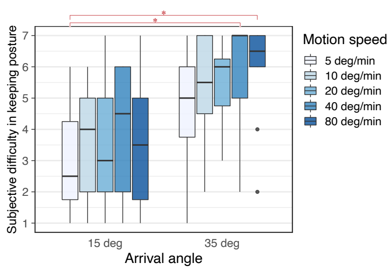


Figure 12: Results of subjective difficulty of maintaining posture in E2.

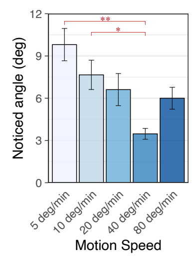


Figure 13: Results of seating angle when the motion was noticed.

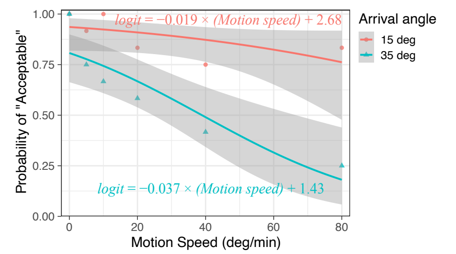


Figure 14: Probability that participants regarded the seating motion as acceptable in E2.

Figure 13 shows the results of seating angle when the participants noticed the motion at each motion speed. Participants did not notice the motion at all in the three trials of 5 deg/min (P3, P4, P7), one trial of 20 deg/min (P2), and one trial of 80 deg/min (P8) at 15-deg arrival angle. The noticed angles of these trials were supplemented with the arrival angle of each motion. In ANOVA, we merged the data under the two arrival angle conditions (since the trials at 35-deg arrival angle could be regarded as inclusive of those at 15-deg arrival) and excluded the trial data in the static seat condition. A one-way repeated measures ANOVA for the noticed angle showed a main effect for motion speed ($F(4, 44) = 5.95, p < .001$). Bonferroni's multiple comparison on the main effect revealed significant differences between 5 and 40 deg/min ($p < .001$) and between 10 and 40 deg/min ($p < .05$). As for the comments on noticeability, at 5 deg/min speed, some participants stated that the angle was changed but unnoticed (P7, P9, P11) or they had difficulty in noticing the change (P8, P10, P12). At 10 deg/min, no one reported that the change was unnoticed, but many participants still expressed it as slow change (P1, P5, P7, P10). In contrast, at the two fastest speeds of 40 deg/min and 80 deg/min, most of the participants mentioned that the motion was fast.

Figure 14 shows the results of subjective acceptability of the motion for each of the seat conditions. We obtained the approximation curves for each of the two arrival angle conditions through binomial logistic regression analyses with acceptability as a dependent variable (Figure 14). The obtained probability at 35-deg arrival was higher than that at 15 deg in all speed conditions, and the analyses showed that the acceptability at 35 deg decreased more sharply with increasing motion speed than that at 15 deg. From the subjective comments regarding acceptability, there were generally few negative ones at 15-deg arrival angle conditions, and there were fairly few comments on physical load and fatigue. In particular, no one complained of interference with the task at 5 deg/min or 10 deg/min speeds. At faster speeds, a few people in each seat condition complained of distraction from the task. In the fastest 80 deg/min speed, some participants felt surprised by the change (P1, P4, P5, P6, P9) or even stopped performing their task (P6). When the arrival angle was 35 deg, most of the opinions were negative. At the slower speeds of 5 deg/min and 10 deg/min, many participants reported physical fatigue and difficulty in maintaining posture (P1, P3, P6, P8, P9, P10, P12) due to the prolonged time spent sitting in a sloped seat. Under the faster speed conditions, many people instead mentioned the difficulty of adapting to sudden change in the seating angle (P1, P2, P4, P5, P8) as well as consequent interruption of their task (P8, P9, P10, P11). Meanwhile, a minority of the participants said that the faster speed was more acceptable because the change was quicker (P3, P12). When asked if they felt unsafe, some mentioned that they felt as if they might slip off under some conditions (P2, P4), while the rest answered that they did not feel any threat to their safety.

4.2.5 E2 Discussion. The results obtained for text-input speed and error rate were not influenced by the seating conditions, which showed the same trends as in E1. These results are noteworthy because **they suggest TiltChair's potential to change seat inclination even during tasks without loss of performance** (although the generalizability of the results needs to be carefully discussed). Only a few participants mentioned that they stopped working (at higher speeds), and they actually stopped for a few seconds at the beginning of the motion. This is one of the reasons that task performance did not decrease even under the faster motion conditions. Lee et al. reported that participants had various reactions to a desk-elevating motion, such as hand gestures and behaviors of observing the motion [33], but we did not observe any such reaction in response to the seat-inclining motion.

Regarding the postural behavior of the participants, both the subjective scores (Figure 12) and our observations clearly show that the difficulty of maintaining posture was greatly influenced by the arrival angle. Together with the results from E1 (Figure 7), it is probable that perceived posture maintenance becomes more difficult as the arrival angle of the inclination motion increases. Therefore, the takeaway from this finding is that **the arrival angle will positively affect the forcefulness that guides the posture to a standing position**.

In contrast, motion speed had a relatively small effect on the change in postural behavior, but instead it was associated with noticeability. Although the present experiments do not reveal the perceptual mechanism for noticing seat motion, our speculation is that under slower speed conditions, the motion was mainly perceived visually as a displacement of the field of view, while at higher speeds, the motion itself was perceived by the tactile or vestibular senses. This might cause the difference in the noticed angle. At the same time, it was also suggested that motion speed affects the acceptability of seat motion to users. This effect was particularly pronounced at the 35-deg arrival angle (Figure 14). This may be due to being surprised at a sudden change and the cognitive and/or physical load required to adjust the posture to the motion. Given these findings, we believe that **the motion speed will positively affect the explicitness and obtrusiveness of the posture guidance to the user.**

One might conclude that the number of participants who actually stood up in the experiment was quite small, given that the purpose of TiltChair is to encourage standing. We believe there are several reasons for this. One major reason is that we did not communicate the purpose of the seat inclination to the participants. Although they were instructed that they could stand up at any time, many comments after the experiment indicated that they resisted the desire to stand up, and some even seemed to mistakenly assume that remaining seated during the task was the implicit goal of the experiment. If users used the system with an appropriate understanding of its purpose, which is to reduce prolonged sitting, we could expect to see an increase in spontaneous standing-up behavior (this is partially investigated in Section 6). Another reason is that the participants were not used to using the sit-stand desk. We speculate that the participants were hesitant to raise the desk height because they were concerned that the time taken to adjust the desk height would delay the task completion. As our future work, the transition to the standing position could be made smoother by elevating the desk height in conjunction with the seat inclination, which is namely an integration with Lee's work [33].

5 DESIGN SPACE FOR POSSIBLE APPLICATIONS

E1 and E2 revealed the fundamental effects of the seat inclination angle and its primitive motions on the user experience. Based on these results, we introduce a design space for effectively facilitating seat-inclination behavior in practical scenarios, with the three dimensions of angle, speed and continuity (Figure 15). Each dimension is defined as follows.

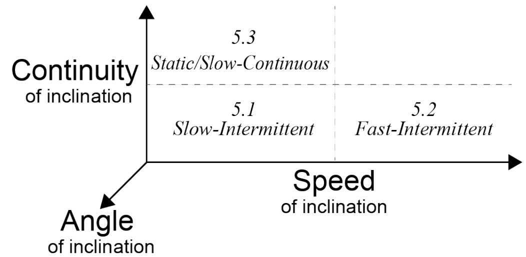


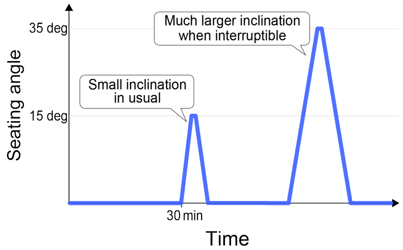
Figure 15: Design space for effectively facilitating seat-inclination behavior with TiltChair.

- **Angle** of inclination has a considerable influence on the difficulty of maintaining posture, which means this dimension could be widely used to achieve situated manipulation in any posture-changing scenario.
- **Speed** of inclination primarily determines the noticeability and subjective acceptability of change to the user, so this could be varied depending on how explicitly (or obtrusively) the user is made aware of the prompt for the posture change.
- **Continuity** of inclination refers to whether the inclination is presented intermittently or continuously. Continuous inclination should generally be avoided due to physical load and fatigue, but it might be advantageous to use it during limited periods for specific purposes.

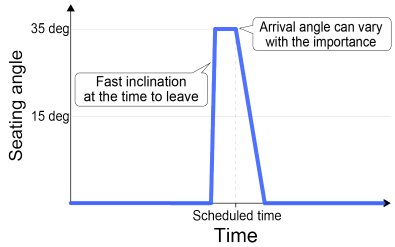
In the following, we discuss several promising applications along with the design space, as shown in Figure 15.

5.1 Slow-Intermittent applications

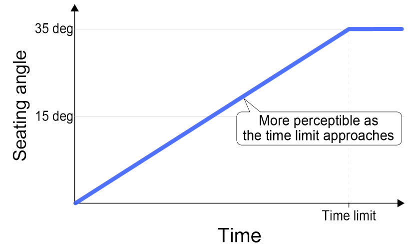
Breaking up prolonged/static sitting. One *slow-intermittent* application is to break up prolonged/static sitting to ensure well-being in office work, which is the main application of TiltChair. Figure 16a shows an example behavior of this application. For this purpose, one basic behavior would be to incline the seat when the system detects a certain amount of static seating duration. In this context, the system should be generally less obtrusive, giving priority to avoiding interruptions of the user's tasks; therefore, the inclination speed should be slow so as not to surprise or distract the user. (Note that E2 results show some people prefer a faster speed, so it might be best to keep the motion speed customizable by the user.) The arrival angle should be carefully situated: for example, a lesser inclination (e.g., 15 deg) is usually presented periodically (e.g., every 30 minutes according to earlier work [15, 44]), and a more forceful inclination (e.g., 35 deg) is presented when the user is more likely to tolerate interruptions. This interruptible timing can be estimated by applying prior work, e.g., using head motion and PC operations [57] or using data retrieved by smartwatches [48]. When the seat inclines to the arrival angle, it should then return to the original angle after a short pause of a certain period (e.g., 1 min). This behavior would allow the user the option of declining a suggestion from the system by simply tolerating the inclination for a while. The behavior (e.g., speed) of returning the angle back, which was not within the scope of this paper, needs to be examined in the future.



(a) Breaking up prolonged sitting



(b) Schedule notification



(c) Time limit representation

Figure 16: Examples of TiltChair behavior when used for each of the applications

5.2 Fast-Intermittent applications

Schedule notification. A *fast-intermittent* inclination would be appropriate when the priority is to change the posture rather than to avoid interrupting the user's task. An example of this situation would be a schedule notification application that prompts users to leave their seats. Figure 16b shows one of the typical behaviors for this purpose. When the time approaches for a user to leave his/her seat (e.g., due to an upcoming appointment), this application makes the seat incline at an immediately perceptible speed (e.g., 40 deg/min). This behavior would make notifications more noticeable than visual notifications by physically assisting the user's action to leave the seat. In addition, the system can change the arrival angle according to the importance of the scheduled event, so that more forceful inclination is applied to more important appointments.

Drowsiness notification. Another example would be to arouse the user from sleepiness while seated. Prior works have explored methods for estimating the seated person's sleepiness (e.g., [22, 42]). With these methods, when the user's estimated drowsiness reaches a certain level, he/she could be awakened at any time by inclining the seat at an immediately perceptible speed (e.g., 40 deg/min). However, one concern is that applying the seat inclination to a drowsy user might impose undue physical/mental stress. Further study is needed to design interactions that can ensure sufficient safety for the user.

5.3 Static/Slow-Continuous applications

Controlling duration of stay. One possible *static/slow-continuous* application is to control the duration of stay by setting the seating angle to a specific position, which can be used for chairs in places where prolonged stays were not originally intended. This idea has already been applied to toilet seats in order to reduce the time spent on them [1]. However, we consider applying it, for example, to chairs in shared meeting spaces. A study has reported that the time spent in standing meetings is shorter than in sitting meetings [10]. In the same way, it would be possible to naturally reduce the time spent on a chair by tilting the seat, e.g., according to the crowdedness in the space.

Representing time limits. A similar application is to implicitly represent the time limit of a task by a *slow-continuous* inclining motion of the seat. Figure 16c shows an example of this behavior. This application is based on the participants' comments in E2, commenting that they felt a sense of urgency as the angle of the seat increases. In general, it is known that task performance improves under a certain time pressure [40]. As the system super-slowly increases the inclination angle of the seat (e.g., at less than 5 deg/min) until the time limit, the user would not perceive it at the beginning, but in the latter part he/she would feel time pressure as physical stimuli (some prior works on this application exploited visual changes [3, 35]), which might improve task performance. Our future work will investigate the effectiveness of this approach for both personal tasks and group-work tasks.

Balancing conversation. Changes in seat inclination might influence social behavior in meeting conversation. Our system will achieve posture guidance tailored to individual users without interrupting meeting interactions. For example, this feature might be applied to balance conversations by controlling the inclination based on users' nonverbal behavior (e.g., speaking time, speaking dominance, gaze exposure, etc.).

Focusing work. The interviews in E1 showed that many users associated the tilt of the seat with the situation of concentrating on work. Thus, one application could be to maintain a specific tilt angle of the seat during the time when the user wants to concentrate. In this context, it would be more appropriate for the user to manually select the tilt angle from pre-defined settings when necessary, rather than automatic control. To the best of our knowledge, no ergonomics or physiology studies have shown an association between the seating angle and concentration, but we believe this issue is well worth investigating in our future work.

6 E3: INITIAL FEEDBACK ON APPLICATION

We conducted E3, an initial user test on a TiltChair application of breaking up prolonged sitting; it was designed to follow the discussion in the previous section. Four students in our laboratory (three males and one female, mean age: 23.5 (SD=1.00), referred to as U1-U4) participated in the test. They knew about a part of this study, but they were never engaged in it themselves. They sat in TiltChair in front of a sit-stand desk and performed their usual work for several hours, while they could freely leave the seat as usual. Seating or not was detected by a threshold of the pressure sensor under the seat, and a small inclination (15-deg arrival at 5 deg/min speed, 1-minute stationary) was presented after 30 minutes of continuous seating and a large inclination (35-deg arrival at 5 deg/min speed, 1-minute stationary) after 1 hour. Before the trial, the participants were given a brief explanation of the behavior of the seat motion and the trial's purpose of breaking up prolonged sitting. After completion of the experiment, they provided us with their comments.

The total working time per participant was 4.50 ± 0.577 hours. Their work consisted mainly of composing documents, reading

[1] https://www.standardtoilet.net/

papers, programming, and participating in online meetings. An average of 4.75 (SD=1.26) small inclinations and 0.750 (SD=0.957) large inclinations were given per user, and they actually stood up 1.50 (SD=1.29) times and 0.25 (SD=0.500) times in response to the small and large inclinations, respectively. They also elevated their desk during the inclination 1.75 (SD=1.26) times on average. As for their perception of the seat motion, three (U1, U2, U4) said they even noticed the small inclination, but one (U3) said he was not very aware of it. They all said that they did not feel distracted by it. When asked if they wanted to use it for their own desk work, they all responded positively. They thought it would help reduce their stiffness (U1, U3), refresh themselves (U2), and avoid falling asleep (U4). These results suggest that **TiltChair's automatic seat inclination can be acceptable and actually promote standing for those who are aware of its purpose**. Furthermore, it was also suggested that even a small inclination might be enough to motivate users to stand up. As a suggestion for improvement, one participant (U2) stated that he wanted to set the time for triggering the seat motion by himself. Two (U1, U2) commented that it would be better to have a function that could immediately cancel the motion.

7 LIMITATIONS AND FUTURE WORK

Effective range of this study. We believe that the two experiments we conducted were adequate to provide initial insights for designing the seat inclining motion. However, the number of participants was not large or diverse enough to build a comprehensive behavior model of the users, given the individual differences observed. In the future, further investigations with a broader range of participants and more detailed seating conditions will be needed. Furthermore, it is not clear that our results are widely applicable to other types of desk work. Although the experiments employed a text-input task, which was relatively simple, more cognitively demanding tasks might make it more difficult for users to accept seat changes, and tasks requiring more precision (e.g., hand writing or drawing) might lead to a direct negative impact on workability. Additionally, we did not compare our approach to many other posture guidance methods. We plan to investigate and summarize the manipulation and acceptability of posture change according to its modality in our follow-up study. Besides, this study does not clarify how our system ergonomically and physiologically interacts with the user to achieve posture guidance. We assume that it involves postural reflex, which is known as a physiological function to maintain postural balance, and we would like to investigate this further.

Another major limitation is that our study does not cover long-term observations. Since prolonged sitting is a habitual behavior, it would be essential to examine the behavioral changes resulting from prolonged use of the system in order to confirm the actual usefulness of our system. At the same time, safety is the highest priority for practical use. E2 results showed that the motion hardly caused any physical danger, but this should also be investigated from a long-term perspective. Therefore, conducting in-the-wild user studies is one of our highest priorities for future work.

Improvements for more practical use. In terms of implementation, the inclination mechanism by pneumatic control was an appropriate way to demonstrate our concept. However, the limitations include the continuous noise from the pump and the low mobility of the entire system. Other methods such as pneumatic or hydraulic cylinder control or shape memory alloy [21] might be suitable for more practical implementation.

In our experiments, we previously confirmed the mechanical stability of the chair as the friction between the floor mat and the wheels prevented it from unintentionally sliding backward. For further safety, however, we might need a minor hardware modification adding a mechanism that locks the wheel's movement during inclination.

Toward practical use of TiltChair, we need to further consider how to mitigate the mental stress and interruption caused by unintentional changes of the seat. As several studies [33, 52, 56] have emphasized, indicating to users that the system is aware of their presence might be beneficial.

This study mainly focused on user experience in response to primitive motions, while many other motion patterns exist (e.g., non-linear velocity changes). In addition, there are many parameters for product design of the chair, including shape, material, and rigidity. Our experiments employed a typical office chair, but the results might have differed somewhat when these parameters are changed. Thus considering ergonomic aspects for the chair design would help reduce physical load during seat inclination. The future work described above, of linking the tabletop height to the seat inclination, would also be a worthwhile pursuit from this perspective.

REFERENCES

[1] Brian P Bailey, Joseph A Konstan, and John V Carlis. 2000. Adjusting Windows: Balancing Information Awareness with Intrusion. In *Proceedings of Conference on Human Factors and the Web*. 39–83.

[2] Gilles Bailly, Sidharth Sahdev, Sylvain Malacria, and Thomas Pietrzak. 2016. LivingDesktop: Augmenting Desktop Workstation with Actuated Devices. In *Proceedings of Conference on Human Factors in Computing Systems*. 5298–5310. https://doi.org/10.1145/2858036.2858208

[3] Yuki Ban, Sho Sakurai, Takuji Narumi, Tomohiro Tanikawa, and Michitaka Hirose. 2015. Improving Work Productivity by Controlling the Time Rate Displayed by the Virtual Clock. In *Proceedings of Augmented Human International Conference*. 25–32. https://doi.org/10.1145/2735711.2735791

[4] Erik A Beers, James N Roemmich, Leonard H Epstein, and Peter J Horvath. 2008. Increasing Passive Energy expenditure during clerical work. *European Journal of Applied Physiology* 103, 3 (2008), 353–360.

[5] Fabiana Braga Benatti and Mathias Ried-Larsen. 2015. The Effects of Breaking up Prolonged Sitting Time: A Review of Experimental Studies. *Medicine & Science in Sports & Exercise* 47, 10 (2015), 2053–2061.

[6] Tom Bendix. 1984. Seated trunk posture at various seat inclinations, seat heights, and table heights. *Human factors* 26, 6 (1984), 695–703.

[7] Tom Bendix, Flemming Bo Jessen, and JØrgen Winkel. 1986. An Evaluation of a Tiltable Office Chair with Respect to Seat Height, Backrest Position and Task. *European Journal of Applied Physiology and Occupational Physiology* 55, 1 (1986), 30–36.

[8] Tom Bendix, JØrgen Winkel, and Flemming Jessen. 1985. Comparison of Office Chairs with Fixed Forwards or Backwards Inclining, or Tiltable Seats. *European Journal of Applied Physiology and Occupational Physiology* 54, 4 (1985), 378–385.

[9] Aviroop Biswas, Paul I Oh, Guy E Faulkner, Ravi R Bajaj, Michael A Silver, Marc S Mitchell, and David A Alter. 2015. Sedentary Time and Its Association with Risk for Disease Incidence, Mortality, and Hospitalization in Adults: A Systematic Review and Meta-analysis. *Annals of Internal Medicine* 162, 2 (2015), 123–132. https://doi.org/10.7326/M14-1651

[10] Allen C Bluedorn, Daniel B Turban, and Mary Sue Love. 1999. The Effects of Stand-up and Sit-down Meeting Formats on Meeting Outcomes. *Journal of Applied Psychology* 84, 2 (1999), 277.

[11] Cynthia Breazeal, Andrew Wang, and Rosalind Picard. 2007. Experiments with a Robotic Computer: Body, Affect and Cognition Interactions. In *Proceedings of ACM/IEEE International Conference on Human-Robot Interaction*. 153–160. https://doi.org/10.1145/1228716.1228737

[12] Lucas J Carr, Hotaka Maeda, Brandon Luther, Patrick Rider, Sharon J Tucker, and Christoph Leonhard. 2014. Acceptability and effects of a seated active workstation during sedentary work. *International Journal of Workplace Health Management* (2014).

[13] I. Daian, A. M. van Ruiten, A. Visser, and S. Zubic. 2007. Sensitive Chair: A Force Sensing Chair with Multimodal Real-Time Feedback via Agent. In *Proceedings of European Conference on Cognitive Ergonomics: Invent! Explore!* 163–166. https://doi.org/10.1145/1362550.1362583

[14] Nico J Delleman, Christine M Haslegrave, and Don B Chaffin. 2004. *Working postures and movements.* CRC Press.

[15] Keith M Diaz, Virginia J Howard, Brent Hutto, Natalie Colabianchi, John E Vena, Monika M Safford, Steven N Blair, and Steven P Hooker. 2017. Patterns of Sedentary Behavior and Mortality in US Middle-aged and Older Adults: A National Cohort Study. *Annals of Internal Medicine* 167, 7 (2017), 465–475.

[16] Soya Eguchi, Yukako Yazaki, Riku Kato, Yusaku Arita, Takumi Moriya, and Hiroya Tanaka. 2020. Proto-Chair: Posture-Sensing Smart Furniture with 3D-Printed Auxetics. In *Extended Abstracts of CHI Conference on Human Factors in Computing Systems.* 1–7. https://doi.org/10.1145/3334480.3383036

[17] Etienne Grandjean, W Hünting, and M Pidermann. 1983. VDT Workstation Design: Preferred Settings and Their Effects. *Human factors* 25, 2 (1983), 161–175.

[18] Diane E Gregory, Nadine M Dunk, and Jack P Callaghan. 2006. Stability Ball versus Office Chair: Comparison of Muscle Activation and Lumbar Spine Posture during Prolonged Sitting. *Human Factors* 48, 1 (2006), 142–153.

[19] Jens Emil Grønbæk, Henrik Korsgaard, Marianne Graves Petersen, Morten Henriksen Birk, and Peter Gall Krogh. 2017. Proxemic Transitions: Designing Shape-Changing Furniture for Informal Meetings. In *Proceedings of Conference on Human Factors in Computing Systems.* 7029–7041. https://doi.org/10.1145/3025453.3025487

[20] Jens Emil Grønbæk, Majken Kirkegaard Rasmussen, Kim Halskov, and Marianne Graves Petersen. 2020. KirigamiTable: Designing for Proxemic Transitions with a Shape-Changing Tabletop. In *Proceedings of Conference on Human Factors in Computing Systems.* 1–15. https://doi.org/10.1145/3313831.3376834

[21] Peter Gust, Sebastian P Kampa, Nico Feller, Max Vom Stein, Ines Haase, and Valerio Virzi. 2018. Intelligent Seating System with Haptic Feedback for Active Health Support. In *Proceedings of the Future Technologies Conference.* 856–873.

[22] Edward O Haeggstrom, Pia M Forsman, Anders E Wallin, Esko M Toppila, and Ilmari V Pyykko. 2006. Evaluating Sleepiness using Force Platform Posturography. *IEEE Transactions on Biomedical Engineering* 53, 8 (2006), 1578–1585.

[23] Thomas R Hales and Bruce P Bernard. 1996. Epidemiology of Work-related Musculoskeletal Disorders. *The Orthopedic Clinics of North America* 27, 4 (1996), 679–709.

[24] Michael Haller, Christoph Richter, Peter Brandl, Sabine Gross, Gerold Schossleitner, Andreas Schrempf, Hideaki Nii, Maki Sugimoto, and Masahiko Inami. 2011. Finding the Right Way for Interrupting People Improving Their Sitting Posture. In *Proceedings of IFIP TC 13 International Conference on Human-Computer Interaction - Volume Part II.* 1–17.

[25] Marc T Hamilton, Deborah G Hamilton, and Theodore W Zderic. 2007. Role of Low Energy Expenditure and Sitting in Obesity, Metabolic Syndrome, Type 2 Diabetes, and Cardiovascular Disease. *Diabetes* 56, 11 (2007), 2655–2667.

[26] Chris Harrison and Anind K. Dey. 2008. Lean and Zoom: Proximity-Aware User Interface and Content Magnification. In *Proceedings of Conference on Human Factors in Computing Systems.* 507–510. https://doi.org/10.1145/1357054.1357135

[27] Haruna Ishimatsu and Ryoko Ueoka. 2014. BITAIKA: Development of Self Posture Adjustment System. In *Proceedings of Augmented Human International Conference.* Article 30, 2 pages. https://doi.org/10.1145/2582051.2582081

[28] Nassim Jafarinaimi, Jodi Forlizzi, Amy Hurst, and John Zimmerman. 2005. Breakaway: An Ambient Display Designed to Change Human Behavior. In *Extended Abstracts on Human Factors in Computing Systems.* 1945–1948. https://doi.org/10.1145/1056808.1057063

[29] Kiyoshi Kiyokawa, Masahide Hatanaka, Kazufumi Hosoda, Masashi Okada, Hironori Shigeta, Yasunori Ishihara, Fukuhito Ooshita, Hirotsugu Kakugawa, Satoshi Kurihara, and Koichi Moriyama. 2012. Owens Luis—A Context-aware Multi-modal Smart Office Chair in an Ambient Environment. In *Proceedings of IEEE Virtual Reality Workshops.* 1–4.

[30] KHE Kroemer. 1994. Sitting (or Standing?) at the Computer. *Hard Facts About Soft Machines: The Ergonomics Of Seating* (1994), 181.

[31] Yoshiki Kudo, Kazuki Takashima, Morten Fjeld, and Yoshifumi Kitamura. 2018. AdapTable: Extending Reach over Large Tabletops through Flexible Multi-Display Configuration. In *Proceedings of ACM International Conference on Interactive Surfaces and Spaces.* 213–225. https://doi.org/10.1145/3279778.3279779

[32] Bokyung Lee, Joongi Shin, Hyoshin Bae, and Daniel Saakes. 2018. Interactive and Situated Guidelines to Help Users Design a Personal Desk That Fits Their Bodies. In *Proceedings of Designing Interactive Systems Conference.* 637–650. https://doi.org/10.1145/3196709.3196725

[33] Bokyung Lee, Sindy Wu, Maria Jose Reyes, and Daniel Saakes. 2019. The Effects of Interruption Timings on Autonomous Height-Adjustable Desks That Respond to Task Changes. In *Proceedings of Conference on Human Factors in Computing Systems.* 1–10. https://doi.org/10.1145/3290605.3300558

[34] James A Levine and Jennifer M Miller. 2007. The Energy Expenditure of using a "Walk-and-work" Desk for Office Workers with Obesity. *British Journal of Sports Medicine* 41, 9 (2007), 558–561.

[35] David Lindlbauer, Jörg Mueller, and Marc Alexa. 2017. Changing the Appearance of Real-World Objects By Modifying Their Surroundings. In *Proceedings of Conference on Human Factors in Computing Systems.* 3954–3965. https://doi.org/10.1145/3025453.3025795

[36] ÅGE C MANDAL. 1976. Work-chair with Tilting Seat. *Ergonomics* 19, 2 (1976), 157–164.

[37] Corinne Mattmann, Oliver Amft, Holger Harms, Gerhard Troster, and Frank Clemens. 2007. Recognizing Upper Body Postures using Textile Strain Sensors. In *Proceedings of IEEE international symposium on wearable computers.* 29–36.

[38] David A McAlpine, Chinmay U Manohar, Shelly K McCrady, Donald Hensrud, and James A Levine. 2007. An Office-place Stepping Device to Promote Workplace Physical Activity. *British Journal of Sports Medicine* 41, 12 (2007), 903–907.

[39] SM McGill, NS Kavcic, and E Harvey. 2006. Sitting on a Chair or an Exercise Ball: Various Perspectives to Guide Decision Making. *Clinical Biomechanics* 21, 4 (2006), 353–360.

[40] Don A Moore and Elizabeth R Tenney. 2012. Time pressure, performance, and productivity. *Research on managing groups and teams* 15 (2012), 305–326.

[41] Bilge Mutlu, Andreas Krause, Jodi Forlizzi, Carlos Guestrin, and Jessica Hodgins. 2007. Robust, Low-Cost, Non-Intrusive Sensing and Recognition of Seated Postures. In *Proceedings of Annual ACM Symposium on User Interface Software and Technology.* 149–158. https://doi.org/10.1145/1294211.1294237

[42] Minoru Nakayama, Keiko Yamamoto, and Fumio Kobayashi. 2008. Estimation of Sleepiness using Frequency Components of Pupillary Response. In *Proceedings of IEEE Biomedical Circuits and Systems Conference.* 357–360.

[43] Kieran O'Sullivan, Mary O'Keeffe, Leonard O'Sullivan, Peter O'Sullivan, and Wim Dankaerts. 2012. The Effect of Dynamic Sitting on the Prevention and Management of Low Back Pain and Low Back Discomfort: A Systematic Review. *Ergonomics* 55, 8 (2012), 898–908.

[44] Meredith C Peddie, Julia L Bone, Nancy J Rehrer, C Murray Skeaff, Andrew R Gray, and Tracy L Perry. 2013. Breaking Prolonged Sitting Reduces Postprandial Glycemia in Healthy, Normal-weight Adults: A Randomized Crossover Trial. *The American Journal of Clinical Nutrition* 98, 2 (2013), 358–366.

[45] Florian Perteneder, Kathrin Probst, Joanne Leong, Sebastian Gassler, Christian Rendl, Patrick Parzer, Katharina Fluch, Sophie Gahleitner, Sean Follmer, Hideki Koike, and Michael Haller. 2020. Foxels: Build Your Own Smart Furniture. In *Proceedings of International Conference on Tangible, Embedded, and Embodied Interaction.* 111–122. https://doi.org/10.1145/3374920.3374935

[46] Kathrin Probst, Michael Haller, Kentaro Yasu, Maki Sugimoto, and Masahiko Inami. 2014. Move-It Sticky Notes Providing Active Physical Feedback through Motion. In *Proceedings of International Conference on Tangible, Embedded and Embodied Interaction.* 29–36. https://doi.org/10.1145/2540930.2540932

[47] Harpreet Sareen, Udayan Umapathi, Patrick Shin, Yasuaki Kakehi, Jifei Ou, Hiroshi Ishii, and Pattie Maes. 2017. Printflatables: Printing Human-Scale, Functional and Dynamic Inflatable Objects. In *Proceedings of Conference on Human Factors in Computing Systems.* 3669–3680. https://doi.org/10.1145/3025453.3025898

[48] Florian Schaule, Jan Ole Johanssen, Bernd Bruegge, and Vivian Loftness. 2018. Employing Consumer Wearables to Detect Office Workers' Cognitive Load for Interruption Management. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 2, 1, Article 32 (March 2018), 20 pages. https://doi.org/10.1145/3191764

[49] Joon Gi Shin, Doheon Kim, Chaehan So, and Daniel Saakes. 2020. Body Follows Eye: Unobtrusive Posture Manipulation Through a Dynamic Content Position in Virtual Reality. In *Proceedings of Conference on Human Factors in Computing Systems.* 1–14. https://doi.org/10.1145/3313831.3376794

[50] Joon-Gi Shin, Eiji Onchi, Maria Jose Reyes, Junbong Song, Uichin Lee, Seung-Hee Lee, and Daniel Saakes. 2019. Slow Robots for Unobtrusive Posture Correction. In *Proceedings of Conference on Human Factors in Computing Systems.* 1–10. https://doi.org/10.1145/3290605.3300843

[51] Nipun Shrestha, Katriina T Kukkonen-Harjula, Jos H Verbeek, Sharea Ijaz, Veerle Hermans, and Zeljko Pedisic. 2018. Workplace Interventions for Reducing Sitting at Work. *Cochrane Database of Systematic Reviews* 6, Article CD010912 (2018).

[52] David Sirkin, Brian Mok, Stephen Yang, and Wendy Ju. 2015. Mechanical Ottoman: How Robotic Furniture Offers and Withdraws Support. In *Proceedings of Annual ACM/IEEE International Conference on Human-Robot Interaction.* 11–18. https://doi.org/10.1145/2696454.2696461

[53] Leon Straker, James Levine, and Amity Campbell. 2009. The Effects of Walking and Cycling Computer Workstations on Keyboard and Mouse Performance. *Human Factors* 51, 6 (2009), 831–844.

[54] Ryo Suzuki, Ryosuke Nakayama, Dan Liu, Yasuaki Kakehi, Mark D. Gross, and Daniel Leithinger. 2020. LiftTiles: Constructive Building Blocks for Prototyping Room-Scale Shape-Changing Interfaces. In *Proceedings of International Conference on Tangible, Embedded, and Embodied Interaction.* 143–151. https://doi.org/10.1145/3374920.3374941

[55] Kazuki Takashima, Naohiro Aida, Hitomi Yokoyama, and Yoshifumi Kitamura. 2013. TransformTable: A Self-Actuated Shape-Changing Digital Table. In *Proceedings of ACM International Conference on Interactive Tabletops and Surfaces*. 179–188. https://doi.org/10.1145/2512349.2512818

[56] Kazuki Takashima, Yusuke Asari, Hitomi Yokoyama, Ehud Sharlin, and Yoshifumi Kitamura. 2015. MovemenTable: The Design of Moving Interactive Tabletops. In *Proceedings of IFIP Conference on Human-Computer Interaction*. 296–314.

[57] Takahiro Tanaka, Ryosuke Abe, Kazuaki Aoki, and Kinya Fujita. 2015. Interruptibility Estimation Based on Head Motion and PC Operation. *International Journal of Human–Computer Interaction* 31, 3 (2015), 167–179. https://doi.org/10.1080/10447318.2014.986635

[58] Shan-Yuan Teng, Cheng-Lung Lin, Chi-huan Chiang, Tzu-Sheng Kuo, Liwei Chan, Da-Yuan Huang, and Bing-Yu Chen. 2019. TilePoP: Tile-Type Pop-up Prop for Virtual Reality. In *Proceedings of Annual ACM Symposium on User Interface Software and Technology*. 639–649. https://doi.org/10.1145/3332165.3347958

[59] C Tudor-Locke, JM Schuna, LJ Frensham, and M Proenca. 2014. Changing the Way We Work: Elevating Energy Expenditure with Workstation Alternatives. *International Journal of Obesity* 38, 6 (2014), 755–765.

[60] Leo L Van Deursen, Jaap Patijn, John R Durinck, Ruud Brouwer, Jeanne R van Erven-Sommers, and Bernard J Vortman. 1999. Sitting and Low Back Pain: The Positive Effect of Rotatory Dynamic Stimuli during Prolonged Sitting. *European Spine Journal* 8, 3 (1999), 187–193.

[61] JHL Van Dieën, MP De Looze, and V Hermans. 2001. Effects of Dynamic Office Chairs on Trunk Kinematics, Trunk Extensor EMG and Spinal Shrinkage. *Ergonomics* 44, 7 (2001), 739–750.

[62] Luke Vink, Viirj Kan, Ken Nakagaki, Daniel Leithinger, Sean Follmer, Philipp Schoessler, Amit Zoran, and Hiroshi Ishii. 2015. TRANSFORM as Adaptive and Dynamic Furniture. In *Extended Abstracts on Human Factors in Computing Systems*. 183. https://doi.org/10.1145/2702613.2732494

[63] Peter Vink, Ineke Konijn, Ben Jongejan, and Monique Berger. 2009. Varying the Office Work Posture between Standing, Half-Standing and Sitting Results in Less Discomfort. In *Proceedings of International Conference on Ergonomics and Health Aspects of Work with Computers: Held as Part of HCI International*. 115–120. https://doi.org/10.1007/978-3-642-02731-4_14

[64] Qi Wang, Marina Toeters, Wei Chen, Annick Timmermans, and Panos Markopoulos. 2016. Zishi: A Smart Garment for Posture Monitoring. In *Extended Abstracts on Human Factors in Computing Systems*. 3792–3795. https://doi.org/10.1145/2851581.2890262

[65] Stephen Wilks, Monica Mortimer, and Per Nylén. 2006. The introduction of sit–stand worktables; aspects of attitudes, compliance and satisfaction. *Applied ergonomics* 37, 3 (2006), 359–365.

[66] Yu-Chian Wu, Te-Yen Wu, Paul Taele, Bryan Wang, Jun-You Liu, Pin-sung Ku, Po-En Lai, and Mike Y. Chen. 2018. ActiveErgo: Automatic and Personalized Ergonomics Using Self-Actuating Furniture. In *Proceedings of Conference on Human Factors in Computing Systems*. 1–8. https://doi.org/10.1145/3173574.3174132

[67] Li Yujian and Liu Bo. 2007. A Normalized Levenshtein Distance Metric. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 29, 6 (2007), 1091–1095.

[68] Nan Zhao, Asaph Azaria, and Joseph A. Paradiso. 2017. Mediated Atmospheres: A Multimodal Mediated Work Environment. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 1, 2, Article 31 (June 2017), 23 pages. https://doi.org/10.1145/3090096

[69] Ying Zheng and John B Morrell. 2010. A Vibrotactile Feedback Approach to Posture Guidance. In *Proceedings of IEEE Haptics Symposium*. 351–358. https://doi.org/10.1109/HAPTIC.2010.5444633

A APPENDIX

Table 1: Participants' behaviors in response to the seat-inclining motion observed in E2 (parentheses show IDs of participants)

Motion speed \ Arrival angle	15 deg	35 deg
Static	Move chair backward (P7)	
5 deg/min	Move chair backward (P5, P8) Change legs' position (P5, P12) Stretch back (P3) Shake upper body (P4) Raise upper body (P12)	Move chair backward (P5, P6, P11, P12) Stretch back (P4, P7, P8) Change legs' position (P4, P5, P7) Raise desk height (P11, P12) Lean forward (P5, P8) Raise upper body (P1) Move laptop forward (P5)
10 deg/min	Shake head (P2) Change legs' position (P6) Stretch back (P7) Move chair backward (P8) Move chair forward (P12) Raise upper body (P12)	Move chair backward (P6, P8, P11) Stretch back (P3, P4, P7) Change legs' position (P2, P4, P7) Raise desk height (P11, P12) Move laptop forward (P5) Change sitting position (P6) Shake upper body (P8) Lean forward (P10)
20 deg/min	Move chair forward (P7, P11, P12) Change legs' position (P4, P12) Stretch back (P4) Lean forward (P8) Move chair backward (P8) Raise upper body (P12)	Move chair backward (P1, P5, P6, P8, P11) Change legs' position (P4, P5) Raise desk height (P11, P12) Stretch back (P4) Move laptop forward (P5) Change sitting position (P6) Raise upper body (P7)
40 deg/min	Change legs' position (P4, P9) Move laptop forward (P5) Stretch back (P7) Move chair backward (P8) Raise desk height (P11) Move chair forward (P12) Raise upper body (P12)	Move chair backward (P1, P2, P5, P6, P8, P9, P12) Stand up (P6, P8) Raise desk height (P11, P12) Shake upper body (P8, P9) Raise upper body (P7) Move laptop forward (P8) Change legs' position (P12) Lean forward (P12) Change sitting position (P12)
80 deg/min	Lean forward (P5) Move laptop forward (P5) Move chair forward (P7) Raise upper body (P7) Change legs' position (P12)	Move chair backward (P2, P5, P6, P7, P8, P9, P11, P12) Move laptop forward (P3, P5, P12) Stretch back (P3, P8) Stand up (P6) Lean forward (P8) Raise desk height (P12)