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Affective Stroking: Design Thermal Mid-Air Tactile for Assisting People in Stress Regulation

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Abstract: Haptics for stress regulation is well developed these years. Using vibrotactile to present biofeedback, guiding breathing or heartbeat regulation is a dominant technical approach. However, designing computer-mediated affective touch for stress regulation is also a promising way and has not been fully explored. In this paper, a haptic device was developed to test whether the computer-mediated affective stroking on the forearm could help to assist people in reducing stress. In our method, we used mid-air technology to generate subtle pressure force by blowing air and generating thermal feedback by using Peltier elements simultaneously. Firstly, we found intensity and velocity parameters to present comfort and pleasant stroking sensations. Afterward, an experiment was conducted to find out whether this approach could help people mediate their perceived and physiological stress. A total of 49 participants were randomly assigned to either a Stroking Group (SG) or a Control Group (CG). Results showed that participants from SG felt more relaxed than those from CG. The physiological stress index, RMSSD, increased and LF/HF decreased in SG although these changes were not statistically significant. Our exploration created subtle, non-invasive, noiseless haptic sensations. It could be a promising alternative for assisting people in stress regulation. Design implications and future applicable scenarios were discussed.

Keywords: mid-air; thermal; haptic; tactile; affective touch; computer-mediated stroking; heart rate variability; stress reduction; digital health; human–computer interaction

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1. Introduction

1.1. Background

In everyday life, people encounter various stressors, eliciting people's anxiety feelings. In the field of human–computer interaction (HCI), researchers have developed technological devices and systems, such as guided breathing [1], biofeedback for reflection [2], relaxation training through biofeedback [3,4], and tools for aiding meditation [5] to help individuals reduce stress and regulate emotions. The mainstream methods of stress regulation typically employ visual [1–4] and auditory [5,6] stimuli. In recent years, a growing body of research has been examining the role of haptics. In the context of haptic-based stress regulation, most cases involve vibrations or pressure sensations used to guide breathing rhythms [7–9], reflect heartbeat rhythms [10–13], or use tactile sensation to present biofeedback to relax [14] and ease anxiety [15]. However, the current haptic sensation is relatively simple, resulting in a monotonous tactile display form, and there is no way to create a more detailed tactile experience. Meanwhile, these haptic actuators generated mechanical noise, affecting the overall user experience.

Touch is a primary non-verbal communication channel for conveying intimate emotions and it is essential for our physical and mental well-being [16,17]. In the appropriate context, non-harmful touch can not only reduce physiological stress indicators, such as heart rate, blood pressure, and cortisol levels, but also enhance heart rate variability. It can also increase levels of oxytocin, serotonin, and dopamine, which are linked to positive emotional states and overall well-being. Moreover, this type of touch can reduce sympathetic nervous activity linked to stress and anxiety [18–23]. Humans, compared to other species, have specialized nerve fibers (CT afferents) that are highly sensitive to gentle, warm, and caress-like touch, yielding positive emotional and physiological effects [24]. Prior research has shown that touch can support emotional regulation through affective touch, which includes gentle stroking characterized by slow, warm movements. This form of touch has been proven to promote secure attachment [25–27]. Other studies also proved that affective touch led to a reduction in autonomic responses and anxiety levels, indicating a calming effect [28]. Touch could be taken as "comforting or caring". Offering comfort is a vital prosocial behavior, which is frequently manifested through affiliative touch directed at individuals in distress, providing alleviation from their troubled state [29]. Usually, individuals who receive affective touch, experience three stages of emotion regulation [30]: situation modification, attentional deployment, and cognitive reappraisal (feeling closeness, connection, and support). This process helps to alleviate anxiety and stress through both external assistance and personal effort.

1.2. Studies About Affective Touch

Affective touch occurs when in contact with the skin [31]. Research in the field of neuroscience has found that CT afferent fibers are closely linked to encoding the emotional aspects of pain, itch, and tickle, as well as sensations of roughness and pleasantness [32]. Additionally, the emotional responses to touch differ between hairy and glabrous skin areas [33]. Two key factors influencing CT afferents are the intensity and speed of the stimulus. Generally, gentle, slow, and light movements are associated with more pleasant experiences compared to firmer strokes [34], and rough surfaces or rapid movements are perceived as less pleasant compared to smooth surfaces [35]. The rating of pleasantness for brush stroking gestures is greater when the stroking velocity is optimal for activating CT afferents (e.g., 3 m/s), compared to other velocities [36]. Temperature sensations are also linked to the mechanisms underlying the perception of pleasantness. People are more likely to accept caress-like touches that are similar to their own body temperature, approximately around 32 °C [37].

1.2.1. Different Actuation Technologies to Imitate Pleasant Stroking

In the field of Human–Computer Interaction, many studies focus on using different actuation technologies to reproduce CT stroking. The common approach is using vibrotactile stimulation. With varying intensity, frequency, velocity, and direction of motion, researchers generate pleasant sensations, similar to real touch [38–40]. Jukka Raisman et al. also found the more continuous the stimulation, the more pleasant it was and the lower the arousal level [41].

In addition, studies have used SMA or voice coil to generate mechanical movement on the skin, thereby producing a feeling of pressure or friction and providing pleasant and natural sensations [42–44]. Lawrence H. Kim et al. studied the VPS (Vibration, Pressure, and Shear) display and found that participants rated the shear mode the highest pleasantness and continuity [45]. Weicheng Wu et al. designed a wearable device consisting of a fabric sleeve and thermoplastic pneumatic actuators arranged in a linear array and found pressure changes during the inflation process did not affect continuity or pleasure [46]. Yiran Zhao et al. developed a wearable device, using synthetic fur which simulated a gentle stroking sensation on the user's forearm. Results showed that participants who received affective touch experienced lower state anxiety and the same physiological stress response level compared to the control group participants. They also found that affective touch facilitated stress regulation by rendering pleasantness, providing emotional support, and shifting attention [47].

1.2.2. Using Mid-Air and Thermal Technology to Influence Affections

Existing technologies have limits for displaying haptic renderings, such as affective touch. The tactile sensations produced by vibration devices are relatively simplistic, often requiring visual assistance to understand the specific haptic gestures [48,49]. Additionally, both vibration and mechanical devices generate noticeable noise [43], which affects the ability of mediated touch to provide a similar experience to human-to-human touch and thus could result in less authentic and skewed emotional expressions. Emerging trends in contactless haptic interfaces are gaining attraction, utilizing mid-air technologies, such as air-jet [50,51] and acoustic radiation pressure [52–55], to generate tactile stimulation without physical contact with the user. Mohamed Yassine Tsalamlal et al. emphasized a significant impact of the air jet's intensity and movement speed on assessments of valence, arousal, and dominance [50]. Marianna Obrist et al. suggested that spatial, directional, haptic characteristics, such as frequency, intensity, and duration of the haptic stimulation, were important factors in generating haptic sensations by employing mid-air tactile stimulation [52]. Sean Chew et al. found that users could directly experience the applications without the need to wear any devices, enhancing the speed and hygiene of the experience [53]. What is more, mid-air tactile is a new promising technology used for stress regulation. Yuka Sato et al. assessed how users perceive haptic stimuli created by air vortex rings applied to the cheek and examined their impact on physiological responses. The findings indicate that specific stimuli may help alleviate stress [51]. In the field of VR, researchers have explored the effect of combining mid-air technology with thermal haptics to create a better immersive experience [55].

Researchers have also found a fundamental link between temperature and intimacy [56], social connections [57], social closeness [58], trust [59], and a warm personality [60]. Furthermore, psychotherapy research shows that warm hands in clients are linked to emotional security [61]. Participants thought these thermal sensations were comfortable and felt like human touch. In the HCI community, thermal touch technologies created thermal sensations of heat or cold. Many studies have shown that temperature affects both the valence and arousal of emotions [62–64]. Warm stimuli are perceived as more pleasant/positive compared to cold stimuli, and both emotional valence and arousal are influenced by modifying the rate or degree of temperature change [62]. Using thermal tactile for stress regulation has become more and more popular. Some works have focused on using heat to guide participants to pay attention to themselves [65] and engage in physical meditation [66] or relaxation [67]. Muhammad Umair et al. designed a personalized thermal tactile module for affect regulation following stress induction in participants [68]. The results showed that thermal tactile feedback effectively helped regulate stress and anxiety, playing a crucial role in the process. Individuals use the perceptual attributes of thermal patterns, along with emotional interpretations and metaphors, to attribute familiar meanings to thermal patterns. However, presenting temperature strokes is technically challenging. Yuhu Liu introduced a haptic device designed to generate a stroking sensation on the forearm by simultaneously applying pressure and thermal feedback. The compact and soft device employs micro blowers and inflatable pouches to create a pressure sensation while utilizing water to provide thermal feedback. According to a user study, it effectively simulated a thermal stroking sensation, and it was observed that cooler temperatures enhanced the perceived pleasantness of the stroking [69].

1.3. Scope of Our Research

A substantial number of haptic technologies have been developed to simulate the sensation of stroking, yet the exploration of combining mid-air and thermal tactile technologies remains relatively limited. Also, few cases use the combination to simulate affective touch to assist stress regulation. A large number of blank areas have yet to be verified. We emphasize mid-air and thermal tactile technologies for stress regulation due to their experiential and material qualities, such as convenience to proceed, comfort, subtlety, ability to direct attention, gradual nature, and privacy. We believe that combining mid-air and thermal feedback can create a comfortable and pleasant stroking experience, further helping users alleviate anxiety and support stress regulation. Compared to other affective touch gestures, such as hugging or patting, which require more complex hardware, stroking demands lower technical complexity. Additionally, stroking can maximize the potential of mid-air technology by simulating a gentle and soothing tactile experience, which is more effective for alleviating stress and anxiety. For the body part selection, we chose the forearm. The forearm is the most extensively studied body part, providing a solid foundation of previous research [38–47,50,53]. Moreover, it is one of the most commonly and easily touched body parts, offering significant potential for developing various corresponding devices. This paper explores affective touch technologies based on mid-air technology, combining thermal sensation for personal stress regulation. We defined research questions as follows:

- How can designs utilize mid-air and thermal tactile technology to create a sensation of being caressed and evoke positive feelings in users?
- What are the effects and impacts of this technology on participants' stress regulation?
- What are other potential applications or scenarios that can adopt this technology?

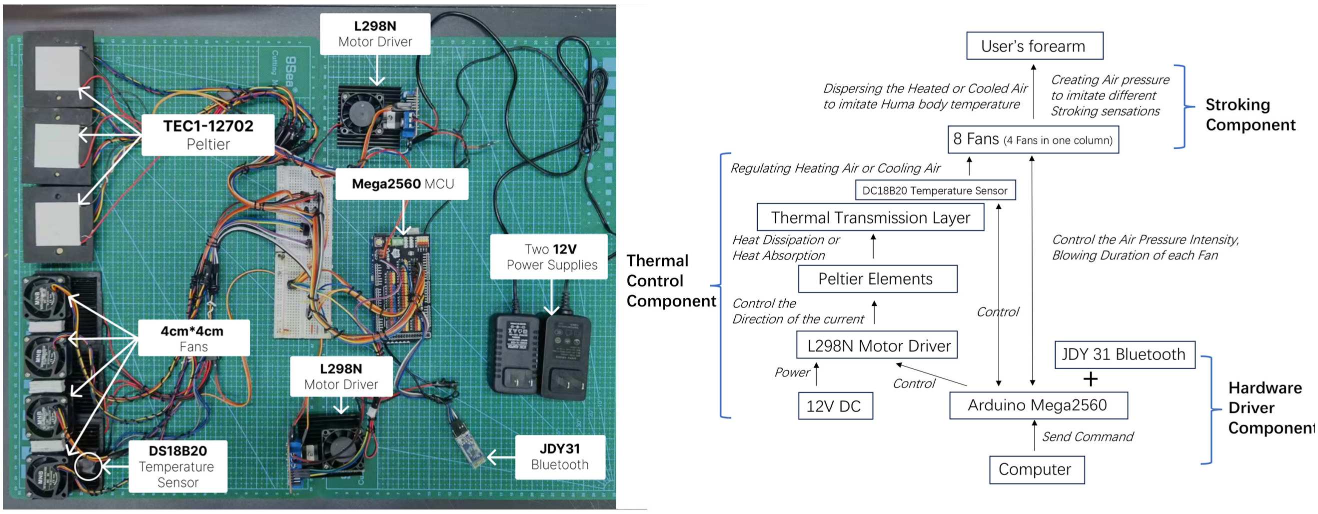
To address these questions, we developed a haptic stroking simulation device. Initially, we evaluated the device to determine the suitable intensity and velocity settings for delivering comforting and pleasant stroking sensations. Subsequently, we conducted a between-group experiment and semi-open interviews with 49 participants. They were randomly divided into either the Stroking Group (SC) or the Control Group (CC). We hypothesized that the computer-mediated stroking device for stress regulation could help to assist people in reducing stress, compared to those who did not use our designed device. After experiencing the stress induction phase, participants who interacted with our haptic device showed a significant reduction in anxiety based on the State-Trait Anxiety Inventory (STAI). The heart rate variability (HRV) feature of those participants also altered, indicating reduced stress and increased relaxation, although the difference was not statistically significant. Our contributions are as follows:

1. We introduce a novel method that creates subtle stroking sensations by combining mid-air and thermal feedback technologies, thereby exploring new design possibilities offered by haptic sub-modalities;
2. We explore design insights of computer-mediated affective stroking, which contributes to the expansion of the design space for stress regulation technologies;
3. We summarize promising design solutions for practical application scenarios, which refine future research and design in mid-air and thermal tactile technologies.

2. Materials and Methods

2.1. Hardware Design and Components

The Stroking Device is composed of three components: the Stroking Component, Thermal Control Component, and Hardware Driver Component (Figure 1). The first component is the Stroking Component, consisting of 8 fans, each measuring 4 cm $\times$ 4 cm. These fans are relatively small and can be combined freely. Therefore, it can be better designed according to the needs of the situation. They are arranged in two columns. Each column contains 4 fans and has a total length of 20.5 cm. The distance between each fan is 1.5 cm. One column is placed on the top of the forearm, while the other is positioned on the outer side (Figure 2). Each corresponding pair of fans from the two columns forms a row, resulting in four rows (P1, P2, P3, P4).



(**a**) (**b**)

Figure 1. Hardware design: (**a**) hardware of the stroking device and (**b**) framework of the whole system.

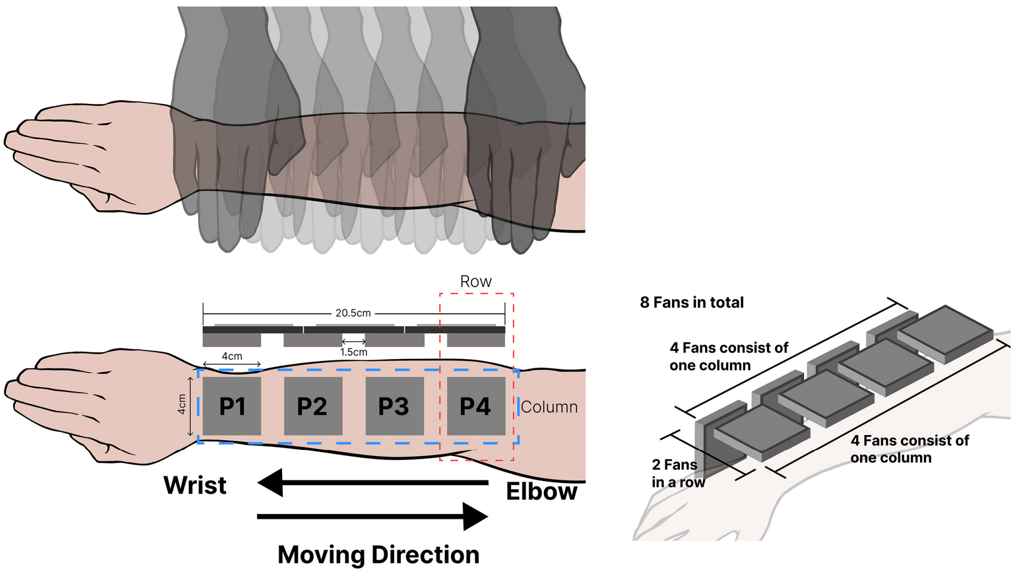


Figure 2. Arrangements of 8 fans and blowing-air pressure on the skin to imitate stroking sensation.

The second component is the Thermal Control Component (Figure 1). Each column of four fans is fixed onto a metal heat conduction layer, which has three Peltier elements (TEC1-12702) attached to its back. Peltier elements have been frequently used as thermal driving devices in previous studies [62–64]. The heat generation and transfer by the Peltier elements are quick and easy. A motor driver (L298N Dual H Bridge) regulates the temperature hot/cold changes in the Peltier elements by controlling the current. Heat is transferred through the conductive layer to the back of each fan. The fan blades disperse the heated air, allowing participants to feel the temperature, thereby simulating the human warmth that should be included in stroking. In this setup, we set the constant temperature to 32 °C [37]. It is within a comfortable temperature range for humans. The DS18B20 temperature sensor detects real-time temperature changes. A PID (Proportional, Integral, Derivative) algorithm is implemented in the software to maintain the temperature at 32 ± 0.5 °C. L298N motor drivers are powered by 12 V power supplies.

The third component is the Hardware Driver Component (Figure 1). Because there are many electronic components, the Mega2560 MCU can provide enough interfaces to ensure the normal operation of the system. We use it to control the fan's blowing speed, the variation in the simulated stroking speed, and the output current of the two motor drivers to manage the thermal changes produced by Peltier elements. Additionally, we develop an Android application that connects to the MCU via a JDY31 Bluetooth module. This allows us to trigger various stroking effects, facilitating participant relaxation based on affective touch in subsequent experiments.

2.2. Computer-Mediated Stroking Design

2.2.1. Parameters of Generating Stroking

Based on previous research [38–40], stroking is a dynamic movement influenced by three factors: the force applied during stroking, the speed of stroking, and the direction of stroking.

Since we use an Arduino Mega 2560 MCU, all control programs are written in Arduino. We translate the stroking force into the intensity of the fan's airflow. In Arduino, the output signal has only two states: high (5 V) and low (0 V). However, many applications require analog signals (signals that can take any value between 0 V and 5 V). PWM (Pulse Width Modulation) simulates an analog signal by adjusting the duty cycle of the high state. By adjusting the duty cycle, we can change the proportion of time the fan motor receives power, thereby controlling the fan motor's speed and, consequently, the intensity of the fan's airflow.

The stroking speed is controlled by the rhythm of the fan's airflow in our device. We group the fans into four rows (P1, P2, P3, and P4). In the Arduino program, only one row of fans blows air at a time, while the other three rows remain off. The blowing sequence is either P1-P2-P3-P4 or P4-P3-P2-P1 (Figure 2). By setting the time intervals for each row's blowing, we control the overall speed of the simulated stroking produced by the device.

$$V = \frac{L}{T}, \quad (1)$$

where L is the length of the device, T is the total duration when our device starts blowing from one end to when it finishes blowing at the other end, and V is the stroking velocity. Since we set the intervals to 1.5 s, 2 s, and 2.5 s. The total duration (T) we set in the Arduino program will be 7.5 s, 10 s, and 12.5 s, respectively. Our device has a total length (L) of 20.5 cm. Thus, the corresponding velocities (V) calculated will be 2.73 cm/s, 2.05 cm/s, and 1.64 cm/s, respectively. Research has shown that the optimal speed for a comfortable stroking sensation on hairy skin is between 1 and 10 cm/s [36,69]. The user's forearm skin will feel the slight pressure from the airflow, and the movement of this pressure across different parts of the forearm creates a continuous sensation similar to stroking (Figure 2). Since the blowing sequence can proceed in two directions, and the device's size generally covers most people's forearms, participants can experience stroking in two directions, either from wrist to elbow or from elbow to wrist.

2.2.2. Pilot Study

The purpose of this study is to test which combination of independent parameter variables can best simulate the effect of stroking, providing users with comfort and a sense of pleasantness. Our experimental device consists of an array of 8 fans arranged in four rows, surrounding the outer and upper sides of the arm (Figure 3). To avoid any potential influence from the experimental device, we used KT boards to make a box that covers the device.

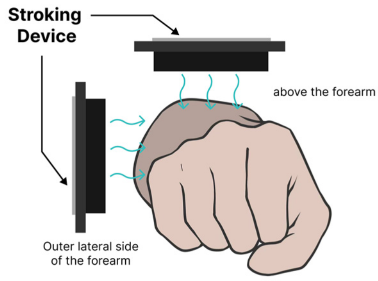


Figure 3. Fans around the outer and upper sides of the arm, blowing air pressure on the forearm.

We designed a 2 ("Moving Direction") × 3 ("Duration") × 2 ("Intensity") repeated measures experiment. The "Moving Direction" variable includes two levels: from the wrist to the elbow, and from the elbow to the wrist. The "Duration" variable refers to the time interval between the activation of adjacent fans, with intervals of 1.5 s, 2 s, and 2.5 s. The "Intensity" variable controls the air force output of the fans using Arduino's PWM, with levels set at "200" and "255."

We recruited 10 participants, including 7 males and 3 females, aged between 23 and 25. All participants were students from a local university. Each participant signed a consent form, agreeing to participate in the experiment and allowing their data to be used for research purposes.

The experiment included 12 parameter combinations based on a 2 ("Moving Direction") × 3 ("Duration") × 2 ("Intensity") design, plus two additional sets without parameters, resulting in 14 sets of wind haptic parameters. These 14 sets were counterbalanced by randomly ordered for each participant to experience.

Upon entering the experimental environment, participants were asked to choose their dominant hand, and the experimenter adjusted the device's position accordingly. Each participant then inserted their arm into the device's box and closed their eyes. During the experience, the participants needed to report whether they felt a stroking sensation and identify the direction of the stroke. They then evaluated each parameter set on four dimensions: perceived continuity, perceived authenticity, perceived comfort, and perceived pleasantness, using a 7-point Likert scale for their ratings. These are the four metrics commonly measured in previous studies on mediated stroking design [41–46]. Participants reported their scores, and the experimenter recorded the data. At the end of the experiment, we conducted a brief semi-structured interview to gather qualitative data from the participants.

2.2.3. Mediated Stroking Design Decisions

Shapiro–Wilk normality tests showed that most participants' ratings are normally distributed ($p > 0.05$). Ratings also met Mauchly's Test of sphericity ($p > 0.05$).

Firstly, Intensity had statistically significant effects on the ratings of continuity and authenticity. It had no statistically significant effects on the ratings of comfort and pleasantness. The ratings for continuity were 4.87 ± 0.29 for PWM_200 and 5.59 ± 0.28 for PWM_255. The ratings for Authenticity were 4.28 ± 0.37 for PWM_200 and 4.88 ± 0.36 for PWM_255. Compared to PWM_200, PWM_255 provides greater power output. Therefore, with increased airflow, the perception becomes more pronounced, resulting in better scores across all evaluation metrics. Secondly, Duration had statistically significant effects on the ratings of continuity, comfort, and pleasantness. It had no statistically significant effect on the ratings of authenticity. Post hoc LSD comparisons showed that there was a significant difference between 1.5 s and 2.5 s on continuity ($p = 0.03$), comfort ($p = 0.01$), and pleasantness ($p = 0.003$). Since the air generated a gentle sensation, the 2.5 s interval provided a longer blowing duration, resulting in a more sustained and stable airflow. This made the perception more pronounced, leading to higher scores across all evaluation metrics. Thirdly, the two-way interaction of Intensity × Duration had statistically significant effects on the ratings of continuity ($F(2, 18) = 5.42$, $p = 0.01$), authenticity ($F(2, 18) = 8.07$, *p* = 0.001), and comfort (F (2, 18) = 5.23, *p* = 0.01). However, it had no statistically significant effect on the ratings of pleasantness (F (2, 18) = 2.11, *p* = 0.15). Figure 4 shows the results. The two-way interaction of Moving Direction x Intensity and the two-way interaction of Moving Direction × Duration did not reveal any significant effects on any of the measured variables. The three-way interaction was not found significant on any dependent variable.

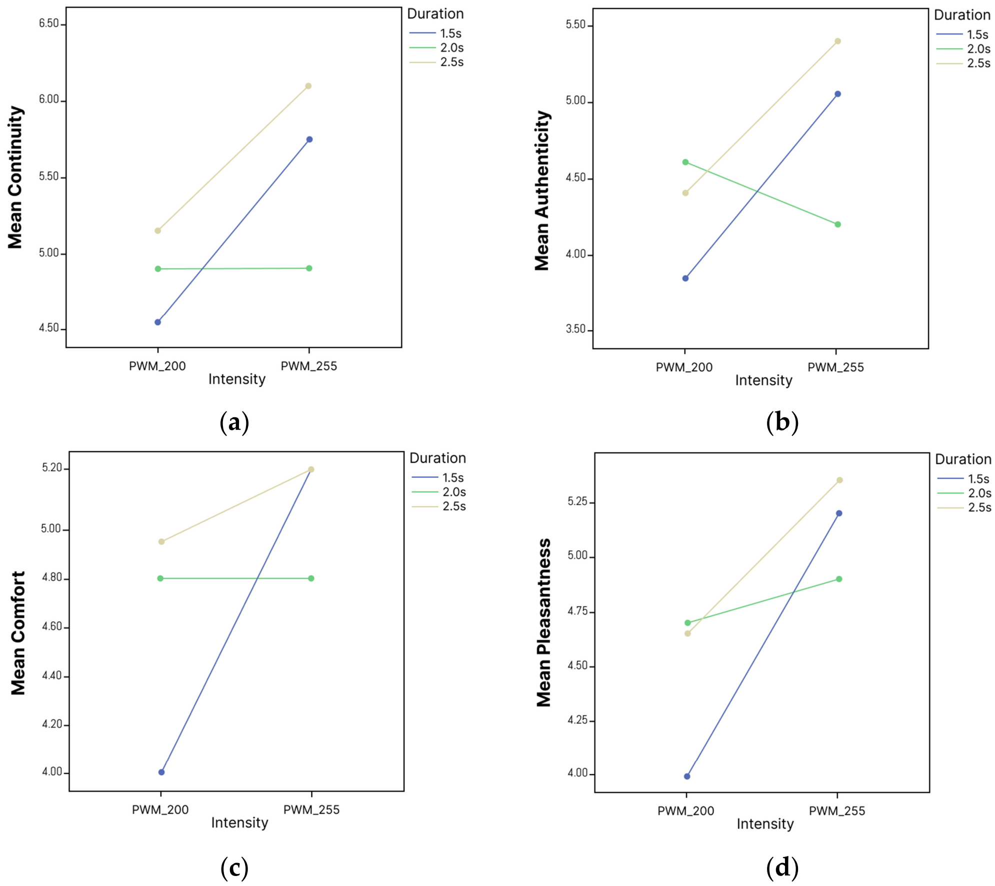


Figure 4. The two-way interaction of Intensity × Duration on four metrics: (**a**) perceived continuity; (**b**) perceived authenticity; (**c**) perceived comfort; and (**d**) perceived pleasantness.

From the study, we can see the intensity of the airflow affects the perception of the stroking force. In our experiment, users felt that the stroking was closer to a gentle human touch when the force was generated by the PWM_255 setting. Additionally, the duration of the interval influences the airflow output, altering the perceived stroking force. The longer the duration is, the stronger the perceived force is. In our study, the 2.5 s interval provided better results across all evaluation metrics. However, due to the varying speeds in real stroking, the 2.5 s interval setting was felt slower. On the other hand, the 1.5 s interval setting resembles the speed of a real human stroking more closely.

We also found that the user's perception of stroking primarily depends on the stroking force and the speed. The higher airflow intensity closely resembles the feeling of actual stroking. Blowing duration also affects the real-stroking perception, but not as important as the intensity. In our study, each fan operated sequentially to create a continuous tactile sensation, with the airflow rhythm being consistently maintained across different stroking parameter sets. The participants could tell the difference in the stroking direction. However, they told us that the Direction of the stroking did not lead to any differences in perceived continuity, perceived authenticity, perceived comfort, and perceived pleasantness for them because the blowing rhythm was fixed.

Considering the above findings, we finally chose PWM_255 as the intensity parameter, with a 1.5 s interval for a fast-stroking effect and a 2.5 s interval for a slow-stroking effect.

The comfort and pleasure provided by the combinations of PWM_255 and 1.5 s interval or 2.5 s interval scored among the highest of all the combinations. We tried the effects of fast-slow stoking cycling and slow-fast stroking cycling within 5 min on the subjects and found that there was not much difference between the two. We decided to use fast-slow stroking as a cycle in the following experiments.

2.2.4. Air Pressure Testing

We further tested the force of air pressure exerted on the skin by a fan under PWM_255 setting for intensity, 1.5 s interval, and 2.5 s interval setting for fast and slow stroking speed. First, we measured the airflow velocity of the fan using an anemometer and then calculated the dynamic pressure using the formula from fluid mechanics. The dynamic pressure is the pressure caused by the airflow when an object is exposed to wind and can be expressed by the following formula:

$$q = \frac{1}{2} \cdot p \cdot v^2, \quad (2)$$

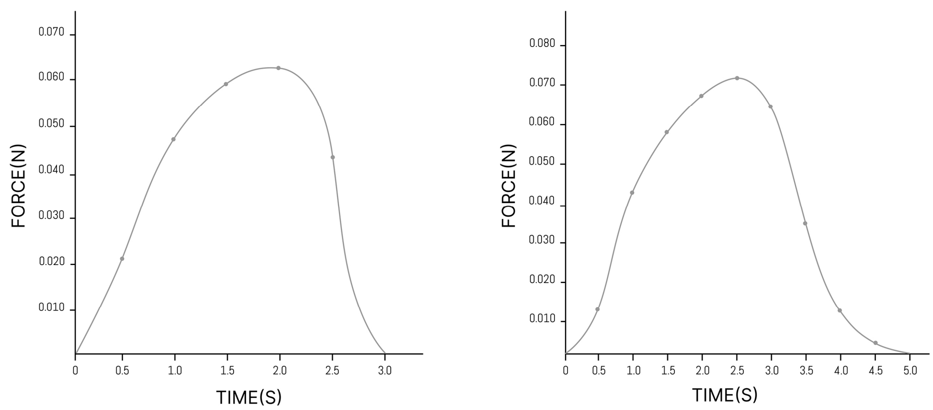
where q is the dynamic pressure, measured in Pascals (Pa); p is the air density, measured in kilograms per cubic meter (kg/m^3), typically around 1.225 kg/m^3 under standard conditions; and v is the airflow speed, measured in meters per second (m/s). Subsequently, the dynamic pressure can exert a force F on the surface of an object, which can be calculated using the following formula:

$$F = q \cdot A, \quad (3)$$

where F is the force, measured in Newtons (N), and A is the surface area of the object exposed to the airflow, measured in square meters (m^2). Substituting the dynamic pressure equation into the formula for force yields:

$$F = \frac{1}{2} \cdot p \cdot v^2 \cdot A, \quad (4)$$

In our case, the surface area of each fan is 0.0016 m^2, which corresponds to the skin area exposed to air pressure. The time intervals were set to 1.5 s for the slow stroking and 2.5 s for the fast stroking, with each fan blowing for durations of 3 s and 5 s, respectively. Figure 5 illustrates the variation of the force generated by a single fan blowing on a fixed skin area for a predetermined duration. The data represent the mean values obtained from three separate measurements.



(**a**) (**b**)

Figure 5. Force generated by a single fan blowing once for 3 s (**a**) and 5 s (**b**).

We compared the air pressure parameter with the pressure parameter caused by human touch. In this instance, we used OKWILL pressure sensors to measure the pressure values exerted on the skin of the human arm by both light and firm real human touches. We also sensed air pressure from our device. The testing durations were set to a predetermined fast stroking time of 7.5 s and a slow stroking time of 12.5 s. As shown in Figures 6 and 7, the pressure data from real human touches fluctuated continuously, whereas the air pressure generated by our device exhibited an initial increase and a decrease at the start and end, respectively, while maintaining relatively stable output in between. The results indicated that the pressure generated by the fan differed from that of a firm human touch, but was relatively similar to that of a light human touch. These results aligned with our expectations, as our goal was to replicate the sensation of gentle stroking and further assess its potential for stress relief in users.

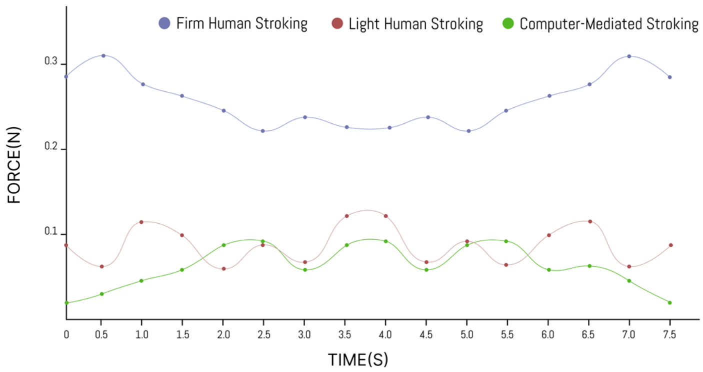


Figure 6. Comparison of pressure parameters caused by air and human touch for fast stroking.

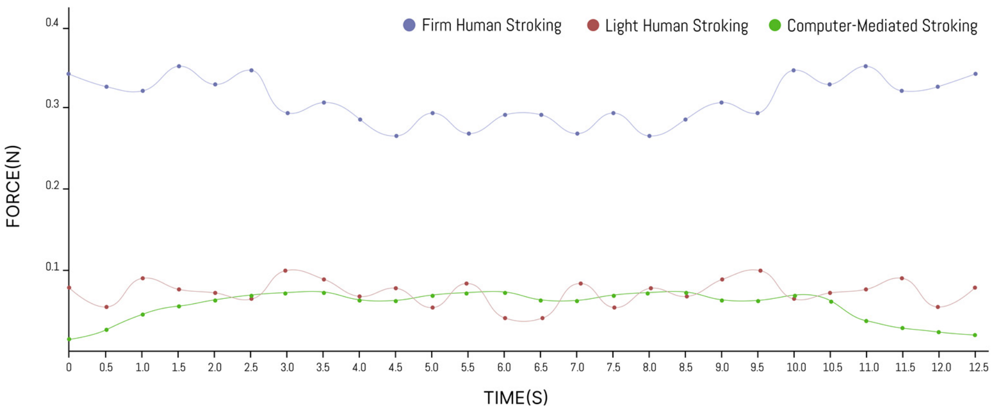
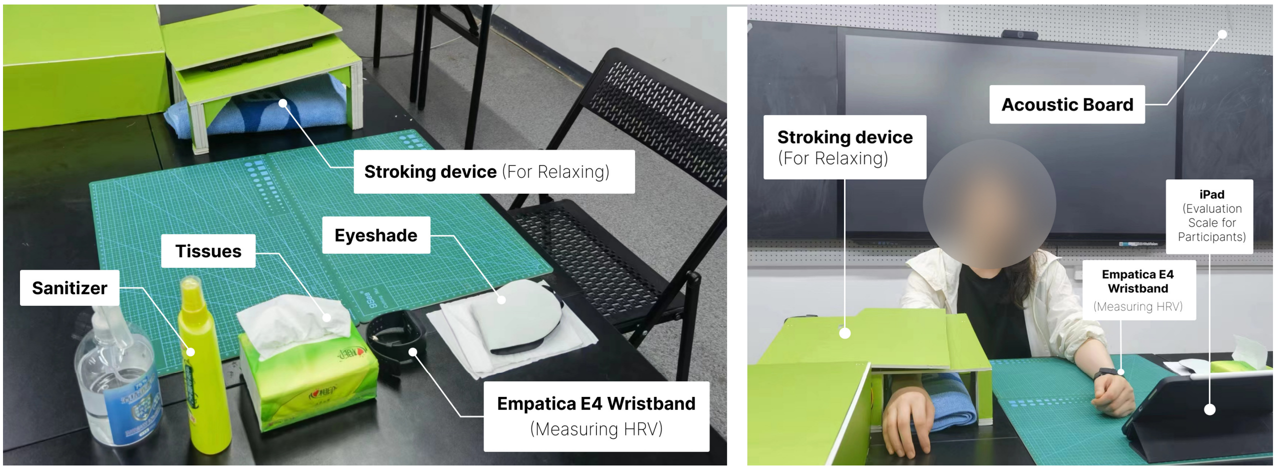


Figure 7. Comparison of pressure parameters caused by air and human touch for slow stroking.

2.3. Experiment Design and Setup

The purpose of this experiment was to evaluate the effectiveness of computer-mediated stroking in reducing stress. The participants were divided into two groups: the Stroking Group (SG) and the Control Group (CG). Both groups carried out a within-subjects experiment, including phases of baseline relaxation, stress induction, and subsequent relaxation. Initially, baseline physiological data were collected for two groups. After obtaining data from the first phase, both groups undergo the same stress induction task. In the final phase, participants from SG relaxed with their eyes closed and received computer-mediated stroking from the device at the same time (Figure 6), while CG only relaxed with their eyes closed.

The experimental room was surrounded by acoustic boards as the experimental environment to avoid noise. The room's windows were equipped with curtains to completely block outside light and prevent potential visual distractions. The experiment took place during the summer, and we used an air conditioner to maintain the room temperature between 22 and 24 degrees Celsius. The lighting in the room was cool-colored light. Inside the room, we arranged the tables and chairs for the experiment. A mat was placed in the center of the table. Since the experiment involved wearable devices, we placed sanitizer and tissues on the left side of the mat for disinfection and cleaning. Since participants needed to close their eyes during the experiment, we also prepared an eyeshade on the left for each participant. The Empatica E4 Wristband (Measuring HRV) was also placed on the left side. On the right side of the mat, we placed the mediated stroking device, covered by a KT board-made box. In front of the participant's seat, we placed an iPad for completing experimental questionnaires (Figure 8). The experiment was approved by the ethics committee from Macau University of Science and Technology (MUST-20230925001).



(**a**) (**b**)

Figure 8. Experiment design: (**a**) experiment setup and (**b**) experiment environment.

2.4. Participants

When selecting participants, we inquired about their physical and mental health. Only those with good overall health were eligible to participate in our experiment. A total of 55 participants (24 males and 31 females) took part in the experiment. Their professions included university students and professors, freelancers, and corporate employees, with ages ranging from 23 to 50 years old. The participants were recruited through Snowball Sampling [70] and they were all right-handed. All participants read and signed informed consent forms before the experiment. They were randomly assigned to either the SG or the CG. In total, 6 participants quit the experiment because they did not want to experience stress induction (doing mathematical tasks) during the experiment or had something interrupted and could not wait until the experiment finished. In the end, the SG consisted of 25 participants, while the CG had 24 participants. In the SG, there were 8 participants (4 males, 4 females) aged 20–29, 8 participants (3 males, 5 females) aged 30–39, and 9 participants (3 males, 6 females) aged 40–49. In the CG, there were 8 participants (3 males, 5 females) aged 20–29, 8 participants (4 males, 4 females) aged 30–39, and 8 participants (4 males, 4 females) aged 40–49 (Table 1). The participants we selected represented the target user group for our design in terms of occupation, age, and gender distribution.

Table 1. The participants were assigned to the experimental conditions.

	Age 20–29			Age 30–39			Age 40–49					
	Males	Females	Total Participants	Males	Females	Total Participants	Males	Females	Total Participants	Total Males	Total Females	Total Participants
Stroking Group (SG)	4	4	8	3	5	8	3	6	9	10	15	25
Control Group (CG)	3	5	8	4	4	8	4	4	8	11	13	24

2.5. Procedure

The experiment consists of three phases (Figure 9), lasting a total of 30–40 min. Before the first phase, participants read and sign an informed consent form, followed by a brief introduction to the experiment. They were equipped with the Empatica E4, which continuously captured their physiological data throughout the experiment.

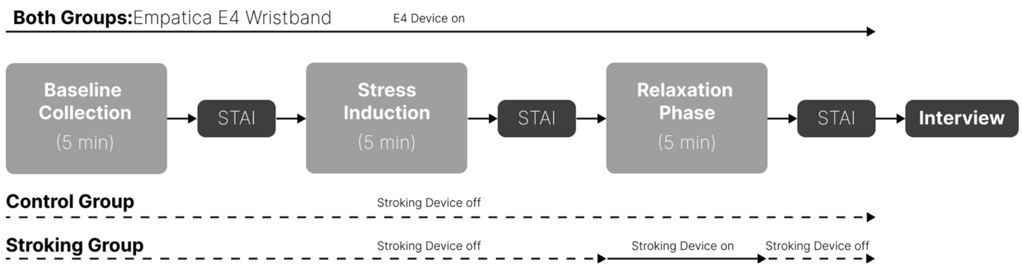


Figure 9. Experiment Procedure.

In the first phase, all participants were asked to sit quietly with their eyes closed for 5 min to collect HRV baseline data. The participants then completed the "state" part of the State-Trait Anxiety Inventory (STAI-S) [71] questionnaire. This phase will last about 10 min.

In the second phase, all participants underwent a 5 min stress induction, details can be seen in Section 2.6. Following this, they completed the STAI-S questionnaire for the second time. This phase was completed within a total of 10 min.

In the third phase, all participants were required to close their eyes and relax uniformly. Members of the SG received an affective touch from a stroking device at the same time, while members of the CG only relaxed with their eyes closed. We applied the fast and slow stroking designed in the pilot study. The stroking protocol was a fast stroking back and forth, followed by a slow stroking back and forth, repeated in a cycle. A total of 15 cycles were performed in 5 min. Both groups experienced 5 min. The participants then completed the STAI-S questionnaire for the third time. This phase was also completed within 10 min.

At the end of the experiment, we also conducted user interviews to collect and analyze qualitative data from the participants. The interpretation of the quantitative findings would be supported by the interview data.

2.6. Anxiety-Inducing Stimulus

The participants of the two groups received an anxiety-inducing event in the form of a mental arithmetic task, after the baseline measures had been taken and prior to the final relaxing intervention. The task [72] required participants to count aloud a reverse counting task starting from 9000 and subtracting 7 each time. This part lasted 5 min.

2.7. Hypotheses

Our experiment hypotheses were as follows:

- Participants who used the computer-mediated stroking device for stress regulation would reduce subjective stress perception more than the control group (H1);
- Participants who used the computer-mediated stroking device for stress reduction were expected to show a greater increase in the physiological indicator RMSSD, compared to the control group (H2);
- Participants who used the computer-mediated stroking device for stress reduction were expected to show a greater decrease in the physiological indicator LF/HF, compared to the control group (H3).

2.8. Measurements

According to previous research [13], due to individual differences, comparing the mean data between groups during the relaxation phase does not effectively reveal the actual impact of the design intervention. Instead, comparing the mean changes in metrics (relaxation phase—stress induction phase) between the SG and CG is a more accurate way to assess the true effect of our design intervention. We used a subjective scale and two physiological indicators as follows:

- State-Trait Anxiety Inventory (STAI);

For this experiment, which focused on short-term changes in anxiety rather than long-term anxiety issues at the individual level, we used the part of "state" of the State-Trait Anxiety Inventory (STAI-S) [71] to collect subjective data from participants at the end of each experimental phase. The questionnaire consisted of 20 items and used a 4-point scale for responses, ranging from 1 ("not at all" or "almost never") to 4 ("very much" or "almost always"), based on the participant's current state.

- Root Mean Square of Successive Differences (RMSSD);

RMSSD [73–75] is a commonly used metric for assessing heart rate variability (HRV). It measures the differences in time intervals between successive heartbeats (RR intervals), reflecting instantaneous changes in heart rate and the ability to self-regulate. In HRV analysis, RMSSD is primarily used to evaluate the activity level of the parasympathetic nervous system, which plays a crucial role in heart rate regulation. An increase in RMSSD indicates heightened parasympathetic activity, often observed during recovery from high-intensity exercise or stressful environments [74,75]. Conversely, a decrease in RMSSD suggests reduced parasympathetic activity, which is associated with higher levels of stress [74,75].

- Low Frequency/High Frequency (LF/HF);

In HRV analysis, LF and HF [76,77] are commonly used frequency domain indicators. The LF/HF ratio is frequently used to assess the balance between sympathetic and parasympathetic nervous system activity. A higher LF/HF ratio may indicate predominant sympathetic activity, which is typically associated with higher stress levels [76,77]. Conversely, a lower LF/HF ratio may suggest a dominant parasympathetic activity, which is generally linked to lower stress levels and better relaxation [76,77].

We calculated HRV metrics from the cleaned RR intervals for each 5 min segment of our experiment [47]. The processing software was Kubios 4.1.1. This 5 min window is selected as it is the widely accepted minimum duration for deriving neurophysiologically significant HRV metric [74].

- Interview.

In our interviews, we addressed eight questions across three parts (Appendix A). The first part (Q1, Q2) focused on the sensory experience and related associations of the computer-mediated stroking itself (with emphasis on the perception of stroking, temperature sensation, comfort, and pleasantness). The second part (Q3–Q6) involved the participants' perceptions during the relaxation phase of the experiment and the impact on individual stress regulation (whether or not it was effective). The third part (Q7, Q8) discussed potential improvements in design features and future usage scenarios. We audio-recorded interviews with each participant. The data were transcribed following the methodology of qualitative content analysis [78]. Two researchers independently transcribed and analyzed the recordings line by line, extracting descriptions relevant to the themes. They named similar events and situations, categorized them, and conducted frequency counts, including the number of participants under each description, to highlight the significance of each theme.

3. Results

We conducted operational checks to determine whether the stress induction phase successfully elicited anxiety states and changes in objective HRV metrics among all participants. The Shapiro–Wilk test indicated that not all subjective and objective measures were statistically normal across three phases. Therefore, we conducted the Wilcoxon test and Mann–Whitney U Test for non-parametric measures and independent samples t-test for the parametric measurement between baseline phase and stress-induction phase. Significant differences were found between these two phases for STAI scores ($p < 0.01$), RMSSD metrics ($p < 0.01$), and LF/HF metrics ($p < 0.01$). During the stress induction phase, we successfully elicited anxiety states in all participants, as evidenced by the decrease in RMSSD and the increase in LF/HF.

3.1. Reduces Subjective Anxiety

We assessed whether our stroking device effectively helped participants relax and alleviate anxiety by comparing the change in STAI scores (relaxation phase—stress induction phase) between the SG and the CG. The Shapiro–Wilk test indicated the change in STAI scores was statistically normal for both groups. An independent-samples T test was conducted to analyze the data. The results indicated a significant difference ($p = 0.045$, two-tailed) between the SG (M = −19.6, SD = 10.50) and the CG (M = −13.38, SD = 9.04). Then, we calculated effect sizes and confidence intervals. Cohen's d was 0.63 and the 95% confidence intervals ranged from −11.43 to −0.14. The result showed the effect size was medium, and the 95% confidence intervals also proved a significant difference between groups. The participants from the Stroking Group felt more relaxed than those from the Control Group (Figure 10). Hypothesis 1 was supported.

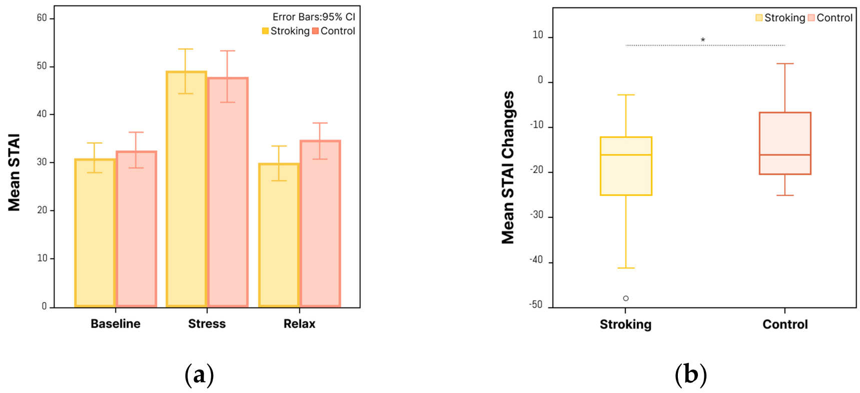
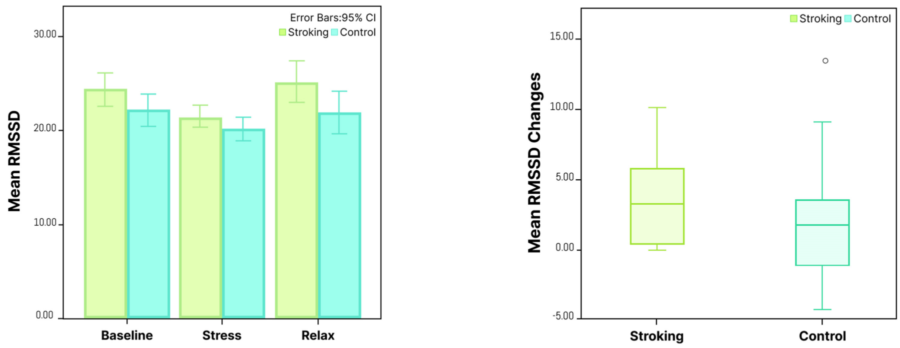


Figure 10. STAI scores: (**a**) mean scores across three phases and (**b**) changes during the relaxation phase. (*: $p < 0.050$).

3.2. Enhances Heart Rate Variability

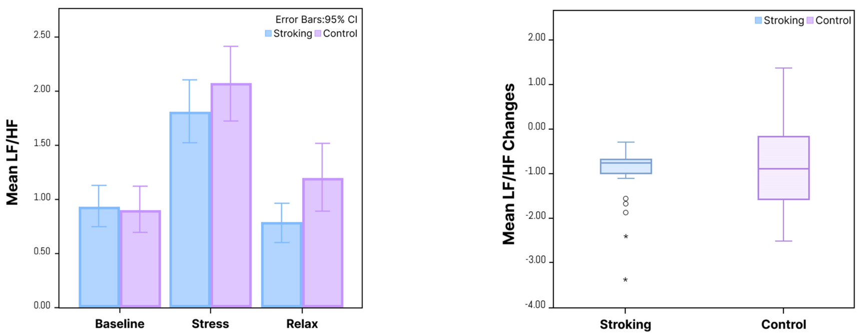
We evaluated whether our stroking device effectively helped the participants relax and alleviate anxiety by examining changes in RMSSD metrics (relaxation phase—stress induction phase) and changes in LF/HF metrics (relaxation phase—stress induction phase) between the SG and the CG. The Shapiro–Wilk test indicated changes in RMSSD metrics and LF/HF metrics were statistically normal for both groups.

An independent-samples T test was conducted on the changes in RMSSD metrics (Figure 11), revealing no significant difference ($p = 0.07$, two-tailed) between the SG (M = 3.65, SD = 3.33) and the CG (M = 1.71, SD = 4.06). Then, we calculated effect sizes and confidence intervals. Cohen's d was 0.52 and the 95% confidence intervals ranged from −0.20 to 4.07. It meant the effect size was medium, while the 95% confidence intervals presented no significant difference between groups. Similarly, an independent-samples T test on the changes in LF/HF metrics showed no significant difference ($p = 0.051$, two-tailed) between the SG (M = −1.03, SD = 0.68) and the CG (M = −0.87, SD = 1.00) (Figure 12). Then, we calculated effect sizes and confidence intervals between groups. Cohen's d was 0.19 and the 95% confidence intervals ranged from −0.65 to 0.33. It meant the effect size was small and the 95% confidence intervals also presented no significant difference between groups.



(**a**) (**b**)

Figure 11. RMSSD metrics: (**a**) mean RMSSD metrics across three phases and (**b**) changes in RMSSD metrics during the relaxation phase.



(**a**) (**b**)

Figure 12. LF/HF metrics: (**a**) mean LF/HF metrics across three phases and (**b**) changes in LF/HF metrics during the relaxation phase. (*: abnormal value).

In all, the results showed that RMSSD metrics increased, and LF/HF metrics decreased in SG, which means our haptic device had a positive effect on participants in improving Heart Rate Variability, although they were not significantly proven. Hypothesis 2 and 3 were denied. We also conducted a three-way ANOVA (gender, age, and group), and found that neither the main effects, two-way interactions, nor the three-way interaction revealed any statistically significant influence of age and gender on the changes in subjective and objective measures.

3.3. Qualitative Results

3.3.1. User's Perception of Mediated Stroking

The majority of participants (20/25) felt the sensation of gentle stroking. Seventeen participants felt it resembled a human's stroking. Three participants compared it to stroking sensations from plush toys, bristle brushes, or curtains. However, five participants thought that it lacked a tangible feeling. Among them, three participants felt it was more like wind and two participants did not think it resembled stroking. Most participants (16/25) like the temperature sensation. They felt the temperature was comfortable and similar to body temperature. Seven participants felt it was slightly warm (with two of them preferring cooler temperatures). One participant found it a bit cool, and one participant felt it was not noticeable.

Almost all participants (22/25) reported the overall feeling is comfortable. However, three participants mentioned a tingling sensation, which was a little bit disturbing. We asked the participants to imagine what kind of emotions were conveyed by computer-mediated stroking. Seven participants mentioned feelings of calmness, tranquility, and relaxation. Nine participants reported feelings of comfort, reassurance, and safety. Three participants felt that the stroking helped them slow down and conveyed gentle emotions. Three participants felt that the machine was trying to communicate with them like a human, expressing care, or even conveying a playful feeling. Three participants did not have any particular associations.

Overall, our design provided participants with a sensation of gentle stroking. Due to the inherently gentle nature of airflow haptics and the addition of body-temperature-comfortable warmth, almost all users reported a positive and comfortable sensory experience. These laid the foundation for further stress regulation and relaxation.

3.3.2. Users Recalled Positive Experience for Stress Regulation

Regarding whether the mediated stroking evoked positive experiences, the majority of participants (20/25) reported recalling positive and pleasant experiences during relaxation. Among them, seven participants mentioned feeling relaxed before bedtime. P02: "*It felt like the state before sleep, receiving a new kind of hypnotic effect*". Seven participants felt that the simulated touch closely resembled a gentle touch from a real person, evoking experiences from intimate relationships, such as touches from parents or other caregivers during childhood, or emotional touches from romantic partners. P01: "*It reminded me of being stroked as a child and because I am a mom, I usually stroke my baby similar to this sensation*". P22: "*It felt like someone stroking me to sleep, thinking of my grandmother*". P24: "*It felt like when my mother used to hold and pat and stroke me as a child*". P34:" *it feels like my wife is flirting with me*". Two participants reminisced about past experiences with nature. P18: "*When I was a child, there was no air conditioning at home. Lying on the sofa by the window, the breeze would blow the curtains, and they would brush over me. It's a pleasant memory. The stroking was light, barely noticeable.*" P42: "*It reminded me of standing on a grassy hillside, with the wind blowing, lifting my hair*". One participant felt it was similar to a spa experience, which was very pleasant. Three participants found it fun and intriguing, wanting to know what was stroking them. The remaining five participants had neutral emotions, with no significant emotional fluctuations.

Regarding whether the mediated stroking helped with stress regulation, almost all participants (23/25) mentioned that it provided emotional comfort. Concerning their stress regulation and relaxation methods during the relaxation phase, twelve participants mentioned zoning out or dozing off. Ten participants recalled pleasant memories and experiences related to intimate relationships. Four participants focused on the stroking itself. However, two participants felt it had little effect. P16 said: "*my personality tends to be unaffected by external factors*". P12 mentioned: "*He couldn't fully relax because they were preoccupied with thinking about the previous math problems*".

According to the interviews mentioned above, the positive and enjoyable sensory experiences, combined with the recalled positive memories, counterbalanced the negative feelings of stress and anxiety induced by the math test. Affective stroking helped participants to modify the situation, divert attention, and achieve cognitive reappraisal, as part of the emotion regulation strategy [30], alleviating negative emotions. It might contribute to further stress relief and relaxation.

3.3.3. Users Raised Expectations for More Design Details

Fourteen participants provided various suggestions for the further development of the technology and equipment, indicating they would use it if these conditions were met. Among them, four participants suggested integrating it with existing devices, such as massage equipment and office or home furniture. Four participants mentioned the need for more body parts and areas to be covered, such as both arms and eventually various parts of the body. Four participants emphasized user customization. P05: "*Control over the stroking rhythm*". P17: "*The interaction process should be simple*". P18: "*Users should be able to set preferences; for example, I enjoy the feeling of friction with textiles when sleeping. This includes control over force, temperature, and body area*". P37: "*The ability to adjust the air temperature would enhance comfort*". One participant mentioned the need for more detailed usage scenarios, and another suggested designing more touch gestures and combining them with multimodal interactions. The remaining five participants expressed that they might use the technology, with four preferring their own methods, such as exercising, listening to music, or watching videos. One participant mentioned that she would not use the device to relax during stressful situations, but rather to enhance relaxation when she is already in a calm state. Another six participants mentioned that the current device already helps them relax, and they would continue using it without other suggestions. Design needs mentioned by the participants stemmed directly from their individual life experiences, providing valuable insights for our future research directions.

3.3.4. Users' Thoughts About Future Applications and Scenarios

We asked the participants to give more possibilities of using this technology and device in other applications or scenarios, according to their own experiences. Eight participants mentioned applications in gaming, entertainment, movie-watching, exhibition spaces, VR immersive experiences, and multimodal synesthetic experiences. Eight participants suggested integrating the technology with existing devices to aid relaxation and emotional regulation. Examples included scarves, clothing, home furnishings, office desks, car seats, massage chairs, beauty devices, sleep pods, and spa spaces. Six Participants expressed interest in using this technology to imitate humans' or animals' touch for remote communications with their family members and friends. Six participants mentioned it could be used as a relaxation aid during personal psychological therapy. Four participants suggested designing it as a sleep aid device. Three participants mentioned it could be used for personal relaxation and meditation. One participant mentioned that the touch felt like a playful interaction with a robot. This suggests that in the future, this technology could be used to design companion robots that engage in touch-based interactions, potentially addressing social issues such as loneliness. The participants mentioned potential usage scenarios, including homes, medical facilities, elderly care centers, physical therapy settings, workplaces, and car interiors. The participants' diverse opinions suggest that this technology has a wide range of potential applications in the future. A detailed discussion can be found in Section 4.2.2.

4. Discussion

4.1. Why Did the STAI Measurements Not Align with the Physiological Responses?

The results showed participants from the SG significantly felt more relaxed than those from the CG based on STAI measurements. The physiological stress index, RMSSD, also increased more, and LF/HF also decreased more in the SG, compared to the CG. However, the physiological data were not significantly proven. Three possible reasons are as follows:

- The novelty of the device may induce subjective preference in users: Some participants in the SG felt excited by using our novel device. They may have anticipated greater relaxation effects, potentially leading to elevated self-reported relaxation scores that do not necessarily reflect genuine physiological changes;
- The limits of the stress induction method: Real-world stressors are varied. The stress induction task mostly affects cognitive load. In real life, people are affected by lots of emotional-driven situations such as social stress caused by interpersonal relationships. Many participants noted that the anxiety induced by mathematical tasks is temporary, unlike ongoing life stressors. This made it easier for them (no matter which group they were in) to relieve anxiety during the relaxation phase, which may challenge the effectiveness of our design intervention;
- Not enough time for the affective touch to take effect on physiological response: Previous research has shown that the effect of affective touch on parasympathetic activation becomes significant only when participants remain in a stress-free environment for more than 16 min [47]. Our study only proceeded for 5 min for intervention.

Future research should aim to conduct experiments either in the lab with a new stress induction method, or in real-world settings, tracking users' stress regulation behaviors for a period of time. We should also let participants become familiar with the device and then test them to avoid of preference or bias, creating enough time for an affective touch to impact the parasympathetic activity.

4.2. Design Implications

4.2.1. Individual Haptic Sensory Experiences Vary Significantly and User's Needs Differ

Numerous studies have highlighted that touch heavily relies on individualized contextual interpretation. Individual customization to meet specific needs is essential.

- The touch of the skin with different intensities affects the tactile sensation: Because we used mid-air tactile to imitate touch on human skin, most users appreciated the gentle sensation it provided. However, some users felt that the intensity was still insufficient compared to physical touch, lacking a sense of realism. Some participants mentioned that touch is not always at the same intensity. Further design should consider the change in stroking intensity to imitate real touch sensations. Others reported a tingling sensation akin to electric shock. This might be due to the fact that we connected eight fan devices simultaneously, and the MCU's supply voltage and current were insufficient, leading to inadequate power for each individual device. As a result, the airflow was weaker or produced a tingling sensation. Variations in hardware fan specifications might also cause inconsistencies in start-up times during operation, affecting continuity and diminishing the realism of the touch experience. Future designs should find appropriate voltage and current supply, consider the balance between airflow intensity and speed, and test the different sensory experiences they provide to users.
- People like thermal tactile at different individuals' preferences: To simulate human body temperature, we maintained the temperature at 32 ± 0.5 °C. Most users stated that a warm touch makes them feel real. They found this range comfortable and acceptable, while a few expressed contrary opinions, feeling either too hot or too cold. Previous studies have indicated a wide variability in users' temperature perceptions; some users experience pleasure from warmth [62,68], while others find cold temperatures pleasurable [68,69]. Future designs should further explore how variations in temperature intensity and rate affect sensory experiences. Consideration could be given to allowing users to customize the temperature to better suit their individual needs.
- Variations in stroking rhythm provide more real touch sensations: During the relaxation phase, we provided users with a fixed, uniform stroking rhythm, which led some users to perceive it as monotonous, particularly over the course of 5 min. Future designs should incorporate variations in stroking rhythm to enhance user experience. This could include one-directional repetitive stroking, bi-directional back-and-forth stroking, or variations in rhythm and pauses during stroking, all of which could contribute to a more authentic stroking sensation. Additionally, offering users the ability to customize their stroking preferences could be considered.
- Considering different body parts and areas for relaxation: Many users felt that applying the touch solely on the forearm was insufficient. They expressed a desire for this tactile experience to extend to more body parts, such as the head and face, and even for a full-body relaxation experience. Our mediated stroking simulation has evoked a sense of relaxation in users reminiscent of various other contexts. These similar experiences have led users to desire that our technology also provide comparable sensations in similar body areas.

4.2.2. Possible Design Directions

Several participants (P02, P05, P08, P22, P24, P29, P31, P41, P42, and P51) became extremely relaxed during the relaxation phase due to our affective touch-based assistance, leading them to either doze off or enter a state of mental blankness. This led them to believe that our technology could be used as a sleep aid. This effect might be attributed to the inherently gentle nature of air-based haptics or possibly because our haptic simulation evokes the comforting experiences of being soothed by caregivers in childhood (as mentioned by many users). We observed a study on using auditory vibrations to aid sleep before bedtime [79], and future research could explore the potential application of using our technology in this context.

Users also expressed a desire to integrate haptics with other modalities. Previous research has suggested that the synchronous integration of haptics with other modalities can better convey emotional experiences [48]. In the experiment, many users mentioned that they preferred to use visual or auditory methods to decompress and relax. Research has shown that combining touch with other modalities, such as sound, can more accurately convey the overall characteristics of the tactile experience [80]. The study and design of haptics in conjunction with other modalities are thus expected to become increasingly important.

Our intermediary stroking simulation has users recall similar relaxation experiences in many other scenarios, leading users to believe that our technology could be effectively combined with existing relaxation and massage devices, or embedded within spa facilities or space for meditation.

Some participants (P05, P11, P17, P29, P34) felt that our rendered touch technology created a sense of interacting with a real person or a robot. Mediated remote emotion communication [81] and emotional haptic interaction with robots [82] are crucial future development areas that merit dedicated exploration and research. What is more, our haptic technology could be taken as haptic feedback and integrated into other technical research programs, such as robot control [83]. It would help facilitate robot design and assist in understanding users' perceptions about interactions with robots.

Regarding the design direction of the user interface or form factors, we see four possibilities: (1) a lightweight design to meet the needs of wearable devices, particularly integrating with traditional clothing items such as hats, scarves, and garments; (2) integration with existing massage instruments, which can be either wearable massage devices like neck massagers or embedded in larger massage equipment such as massage chairs; (3) development of embedded devices that integrate into living spaces, combining with sofas and beds, embedding into workplaces with desks and chairs, or integrating into automotive environments with car dashboards or seats; and (4) combining haptic rendering technology with robotics could enhance robots' ability to engage in social interactions with humans.

4.3. Limitation and Future Work

Firstly, we only used mid-air haptics to simulate a stroking gesture. Further research is needed to determine whether other gestures, such as hugging or tapping, might yield similar or even better stress regulation effects. Secondly, due to time constraints, we were unable to recruit more participants and thus did not compare our approach with other haptic feedback technologies, constraining the understanding of this method's performance. Future research should explore the different impacts of various haptic technologies. Thirdly, some participants mentioned that the temperature of a hand stroking might not always be gentle or warm. Further studies are required to investigate how variations in temperature and the rate of temperature change, as well as differences in the pressure of touch, affect stress regulation. Fourthly, according to the limits mentioned in Section 4.1, we should carefully design our research. Further studies could use other stress-induction methods like TSST to induce social stress [47] or be conducted in the wild based on different stress situations. It is better to conduct longer research and avoid the bias or preference caused by participants for using the novel device. We want to fully test whether our approach could help people or not in stress regulation.

5. Conclusions

In this paper, we designed stroking sensations by using Peltier elements to generate warm air and blow it by an array of fans. Computer-mediated stroking is subtle, comfortable, gradual in nature, noiseless, and private, giving participants comfortable and pleasant sensations, evoking participants positive experiences, and distracting attention from stressful work. The experiment showed that participants in the SG reduced anxiety and felt more relaxed after stress induction by using our haptic device. This novel technology shows the potential for stress regulation and needs to be developed further on detailed parameters, such as intensity and velocity of airflow, temperature variations, and the rate of temperature change, according to specific situations and personal requirements.

This work presents an innovative approach that combines mid-air and thermal feedback technologies, opening up new design possibilities within haptic sub-modalities. It also delves into the design insights of affective stroking, contributing to the expansion of the design landscape for stress regulation technologies. Meanwhile, this work outlines possible design solutions for real-world applications, which will guide future research and development in mid-air and thermal tactile technologies. At last, all discoveries are contributing to the advancement of studies in the field of digital health, promoting people's mental health and well-being.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Ethics Committee of Macau University of Science and Technology (protocol code: MUST-20230925001, 12 June 2023).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Questions of User Interview

Q1: How do you feel about this stroking sensation? (Does it feel like a gentle stroking? How does the temperature feel? How comfortable is the sensation?)
Q2: How do you interpret this stroking and the emotions it conveys?
Q3: What kind of experience does this stroking provide?
Q4: Does the stroking evoke positive and pleasant feelings?
Q5: Does the stroking help to provide emotional comfort?
Q6: What is your personal stress regulation method during the relaxation phase?
Q7: If the prototype were further developed, would you be inclined to use this feature to assist with stress regulation in the future?
Q8: What other scenarios do you think this feature could be useful for?

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