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Sitting comfort in an aircraft seat with different seat inclination angles

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ABSTRACT

Passengers' comfort experience during flights is important in choosing their flights. The focus of this study is passengers' perceived comfort in different climbing angles during ascent. Twenty-six participants were invited to experience three inclination angles including 3°, 14° and 18° in a Boeing 737 cabin. The angle of 3° was used to simulate cruising stage and the other two were used to simulate different climbing angles. Participants experienced each setting for 20 min where the perceived comfort, their heart rate variability(HRV), and their body contact pressure values on the backrest and seat pan were recorded with questionnaires, HRV bands and pressure mats respectively. The results indicate a preference of 14° inclination angle resembling the cruising angle (3°) and having the slowest moving speed of the center of pressure (COP) on both the backrest and seat pan.

1. Introduction

Passengers' comfort experience in flights is one of the key elements in selecting airlines (Balcombe et al., 2009). Previous studies have analysed different factors influencing comfort/discomfort, e.g. in-flight service and noise do play a role (Brindisi and Concilio, 2008)(Mellert et al., 2008). Among all aspects, seat comfort is one of the most crucial factors influencing comfort experience in the aircraft cabin (Vink and Brauer, 2011). Comfort sitting during the cruising stage was studied in the literature for instance regarding the seat pitch (Shabila Anjani et al., 2020), seat width (Shabila Anjani et al., 2019), sitting duration (Peter Vink et al., 2017). However, not much literature focuses on the comfort experience of passengers during ascent and descent.

While the plane has gained enough speed during take-off, pilots start to rotate the plane while keeping tail clearance (Pinsker, 1967). After the airplane gains enough speed and altitude, they control the plane to climb with a relatively stable angle until the desired cruising height is reached. This process may take 20–30 min. According to the procedure recommended by Boeing, the climbing angle of a 777 airplane is 14° and the climbing angle of a 737 airplane, which is relatively smaller than 777, varies between 15 and 18° (Wakefield and Dubuque, 2009).

Many factors might influence comfort of passengers during the climb phase, e.g. getting accustomed to the pressurization (Zheng et al., 2015) and the acceleration (Zoccali et al., 2018). Among those factors, the pitch angle of the airplane is important. It is the angle between the longitudinal axis of the airplane and the horizon (Johari et al., 2018). The angle of the airplane causes the seat to tilt backward, and therefore changes the direction of the gravitational force of passengers' body against the seat. Furthermore, in this phase, the backrest of the seat is put upright, and the seat belt is fastened, which might make it difficult for passengers to seek for a comfortable posture themselves.

Previous studies investigated the effects of inclination on the physical state of passengers in sitting and it was suggested that increased muscular activity can happen in the postures with a tilted trunk (Munoz and Rougier, 2011). Cherng et al. (2009) investigated the reaching efficiency of children with inclined seats and found that posterior positions posed a greater postural challenge. A study focusing on wheelchairs stated that tilting the seat forward required less effort from individuals with decreased ability during one-leg wheelchair propulsion (Suzuki et al., 2012). However, effects of seat inclination on the perceived comfort of humans in the context of aircraft cabin is not fully explored.

Passengers' perceived comfort and discomfort can be evaluated with questionnaires (Shabila Anjani et al., 2021). In a previous study, preferences of different questionnaires were studied with researchers and designers. The simple score comfort questionnaire was recommended for evaluating most products, either in the early stage of the design or functional prototypes (Anjani et al., 2021). For instance, Yao et al. (2021) used comfort and discomfort questionnaires to evaluate the influence of different scents on passengers' comfort experience in a Boeing 737 cabin. Hiemstra-van Mastrigt et al. (2015) used the perceived discomfort questionnaire and Local Postural Discomfort (LPD) questionnaire in studying the effects of active seating on car passengers' comfort.

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Beside subjective feelings, researchers also use different objective measures to evaluate comfort of humans (Song and Vink, 2021). Among different measurement methods, pressure map has demonstrated its effectiveness in recording the interaction between the human body and the seats (e.g. (Na et al., 2005)(Braun et al., 2015)(Hartung, 2006) (Lantoine et al., 2022)). Zemp et al. (2015) identified that pressure parameters are potentially capable of describing aspects of comfort. Noro et al. found that low peak pressure and a large contact area of the seat pan are related to comfort (Noro et al., 2012). Akgunduz et al. (2014) confirmed the strong correlation between comfort and the peak and mean pressures. More recently, pressure maps are also used in comfort studies in aircraft seats (Yao et al., 2022).

Heart rate variability (HRV) as a physiological parameter determined by the balance of the vagus and sympathetic nerves, can be used to reflect the physiological changes within the human body (Kataoka and Yoshida, 2005). HRV features including SDSD (Standard deviation of differences between adjacent n-n intervals), SDNN(Standard deviation of the time interval between successive normal heart beats (n-n intervals)),RMSSD (Root mean square of successive n-n interval differences), LF (Low frequency of the heart rate, range .04–.15 Hz), HF (High frequency of the heart rate, range 0.15 to .40 Hz) and LF/HF (Ratio of LF/HF) were used in previous studies as indicators of different emotions (Zhu et al., 2019)(Shi et al. ,2017), and were also applied in comfort studies (Anjani, 2021). For instance, Lorenzino et al. (2020) found that acoustic comfort is greatly determined by psychological processes based on the differences between LF, HF and LF/HF regarding these HRV features. HRV measurement was used in thermal comfort studies as well and it was found that LF/HF varies when the environment temperature changes (Liu et al., 2017)(Zhu et al., 2018).

In this paper, utilizing different subject and objective measures, we aim at finding the influence of inclination angles of the seat on comfort and discomfort. The research question is set as: What are the effects of different inclination angles on comfort/discomfort experience of the passengers during the climbing phases of a flight?

2. Methods

2.1. Experiment setting

To measure the effects of the climbing angle on the perceieved comfort of passengers, an experiment was set up in the Boeing 737 fuselage at the Delft University of Technology (Fig. 1). The experiment setup and the protocol were approved by the Human Research Ethical Committee (HREC) of Delft University of Technology. Fourteen males and twelve females were recruited for this experiment. The mean age is 25.5 ± 2.59 and the average BMI is 22.78 ± 3.3. The seat used in this experiment is a Recaro economy class seat equipped in the 737 aircraft. Recaro is used by different airlines and have been used in several comfort researches (Kremser et al., 2012)(Yao et al., 2021)(Dangal et al., 2021). The width of the seat was 17-inch and the pitch was 30-inch. The seat surface angle is 3-degrees tilted backward with respect to the floor and the backrest recline angle is 105-degrees in the upright position. To simulate the scenario in a realistic context, two rows of seats were used in this experiment while participants sit in the middle of the second row. The seats were mounted to a large platform which can be adjusted to different inclination angles (Fig. 2). According to Wakefield and Dubuque (2009), the smallest and largest climbing angles of most Boeing 737–777 series are 14° and 18° respectively. 14° and 18° were selected to simulate the climbing angles. Since the horizontal tail incidence is usually −3° for the lift coefficient required for cruise condition, 3° was set up for cruise simulation (Nasoulis et al., 2022).

Fig. 1. Participant sitting in the aircraft seat in a Boeing 737 aircraft cabin.

During the experiment, the participants experienced all three setups in a Latin square order and the seat belt was always fastened as well. All participants wore an armband (Brand: Scosche Rhythm24) at the left forearm. Their heart rate and the n-n intervals were logged throughout the experiment continuously. The pressure data both on the seat pan and backrest were recorded with two pressure mats (Brand: XSENSOR Technology, Type: LX210:48.48.02) with a sample rate of 1 HZ. Each pressure mat consists of 48 *48 sensing cells with a dimension of 12.7 mm*12.7 mm.

The Comfort/discomfort questionnaire (11-points Likert scale; 0 = no discomfort at all; 10 = extreme discomfort) was used for recording the perceived overall comfort and discomfort, and it was asked several times in the experiment. To avoid the effect of short term memory the questionnaire was completed while seated, and to avoid the confusion of the word “comfort” and “discomfort” in different languages and cultures (Vink et al., 2021), the wordings in the questionnaires were explained by the researchers prior to the experiment.

2.2. Protocol

The procedure of the experiment can be found in Fig. 3. As the duration of the climbing phase is about 20–30 min (Ping, 2021), participants experienced each set up, i.e. setting 1, 2, and 3, for about 20 min in three sessions. In each session, a participant were asked to complete the comfort/discomfort questionnaire right after sitting down. Then he/she completed the same questionnaire again after 10 min. At

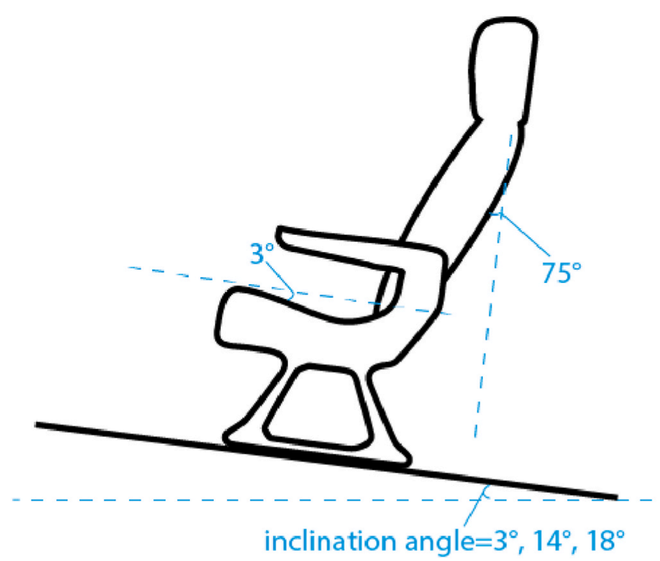

Fig. 2. Schematic diagram of the aircraft seat in the experiment and the settings with three different inclination angles.

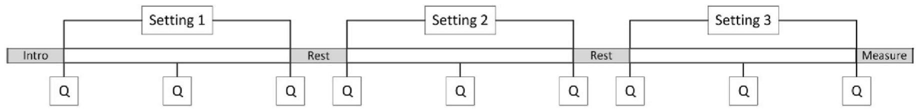

Fig. 3. Procedure of the experiment (Q: participants filling in the questionnaire).

the end of the session, he/she completed the same questionnaires before leaving the seat. A short rest session was set between sessions. During the break, the participant was required to have a rest of 7–10 min and walk along the aisle to "reset" the comfort/discomfort status. The orders of the settings were varied by Latin square orders but procedures were the same. In each setting, the HRV and pressure data were continuously recorded. And finally, his/her stature and weight were measured.

2.3. Analysis

Scores of comfort and discomfort were tested with the Shapiro-Wilk test. Since the scores were not distributed normally, the Wilcoxon Rank test was selected to find out the difference in perceived comfort and discomfort regarding different inclination angles as well as different moments in the experiment.

Fig. 4 illustrates a simplified free body diagram of the forces applied on the passenger. Mean pressure, peak pressure, and contact area on both the seat pan and the backrest in the three different settings were calculated based on the data collected by the pressure mats. The contribution of each part to support the human body in the vertical direction was reported. According to Martinez-Cesteros et al. (2021), COP (center of pressure) can be key to reflect postural stability. Based on the formula used in their study, COPs of the pressure maps both on the seat pan and the backrest were calculated as $\vec{LC} = \frac{\sum_{i=1}^{n} P_i * \vec{L_i}}{\sum_{i=1}^{n} P_i}$, where P_i is the recorded pressure value in a cell, $\vec{L_i}$ is the position vector of the cell, n is the number of the cells in each frame. The speed of the COP movement in each session was computed as $V_C = \frac{\sum_{j=1}^{m-1} |\vec{LC_{j+1}} - \vec{LC_j}|}{(m-1)*t}$, where $\vec{LC_j}$ is the location of the COP in the j^{th} frame, m is the number of frames and t is the time duration between two frames.

HRV features including SDNN, RMSSD, SDSD, LF, HF and LF/HF were calculated with the n-n intervals collected by the armband during the experiment. The HRV data of one participant were excluded due to incompleteness of the three settings. After testing with the Shapiro Wilk test, the normally distributed features in the three settings were compared using a paired samples T-test (two tailed), while the Wilcoxon Rank test was used for other features. Pearson correlations between HRV features and (dis)comfort were reported as well.

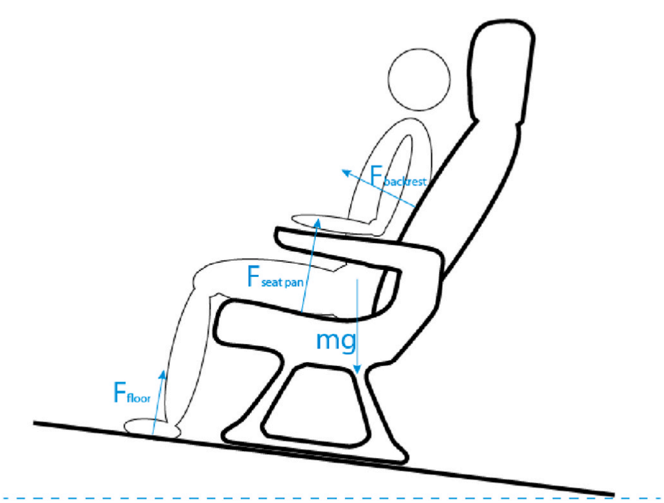

Fig. 4. Approximate free body diagram of passengers sitting in the aircraft seat with an inclination angle.

3. Results

3.1. Comfort

Comfort and discomfort scores are shown in Fig. 5. Significant differences between different settings were marked with dots and significant differences between different time spans in the same setting were connected with dash lines. The figure shows a trend that with the increase of the inclination angle, subjects' perceived comfort decreases and discomfort increases. Sitting in the aircraft seat with an inclination angle of 3° is significantly less discomfort than 18° after 10 min. No significant difference was found between 14-degree setting and the other two settings regarding both comfort and discomfort. No significant differences on the first impression of the three settings were found as well. With sitting time increased, the perceived comfort decreased and discomfort increased. In the 14-degree and 18-degree settings, significant difference was found at the 10th minute with comfort while significant difference in discomfort was only found at the 20th minute. This may indicate that changes on comfort require less time than discomfort.

3.2. Pressure

The values of the mean pressure, peak pressure and contact areas on the backrest are shown in Table 1. The mean pressure and peak pressure on the backrest of the 14-degree and 18-degree settings are significantly higher than that of the 3-degree setting. The contact area on the backrest increased when the inclination angle increased. Table 2 shows the pressure parameters on the seat pan in different settings. It shows that the mean pressure and peak pressure dropped when the inclination angle increased. The changes in contact areas on the seat pan followed the same trend with those on the backrest but only the difference between the 3-degree and 18-degree settings are found significant.

Table 3 shows the force on the backrest and the seat pan in three different settings. Table 4 shows distributions of the vertical force components supporting the weight of the subjects at the backrest, seat pan and floor, respectively. The numbers shown in tables are averaged over 26 participants. As the inclination angle increases, the total force increases. Though the percentage of the supporting force from the backrest increases with the inclination angle, the seat pan still gave the most support in all the three settings. Table 5 shows the COP changing speed in different settings. The COP on the backrest moves slower in the 14-degree seat than in the 3-degree seat. The COP on the seat pan in the 14-degree setting moves with the slowest speed. In the 14-degree setting, COP on the seat pan moved significantly slower in the 18-degree setting.

3.3. HRV

HRV features including SDNN, RMSSD, SDSD, LF, HF and LF/HF of each participant in each setting are calculated, the average values can be found in Table 6. Compared with the 3-degree setting, the LF is significantly lower when participants are sitting with an inclination angle of 18°. The LF/HF of participants in both 14-degree and 18° settings are lower than in the 3-degree setting. The correlations of these features to comfort and discomfort are shown in Table 7. Correlations with p values under 0.05 are considered significant. Significant correlations were

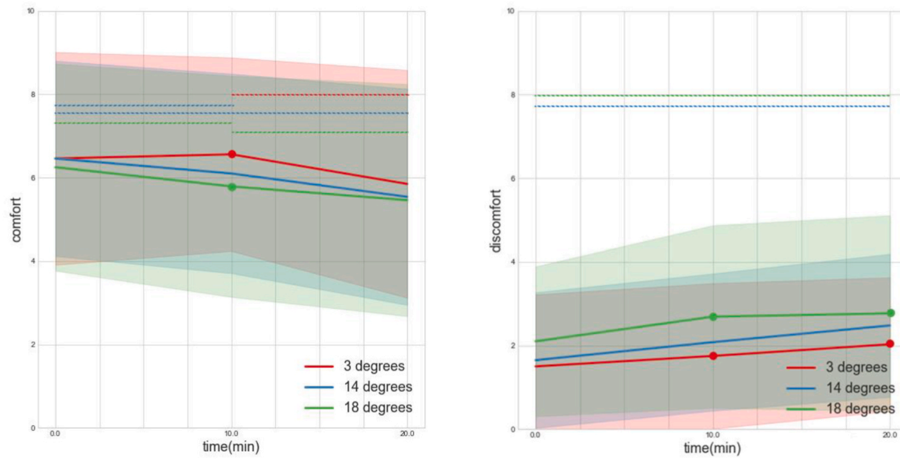

Fig. 5. Absolute scores of perceived comfort and discomfort in 20 min with the standard deviation in a lighter colour (0 = no (dis)comfort at all, 10 = extreme (dis) comfort). Significant differences ($p < 0.05$) between settings at the same points are marked with dots. Significant differences ($p < 0.05$) between time points in the same settings are connected with top horizontal dash lines.

Table 1
Average pressure, peak pressure and contact area on the backrest in three settings. T-test p values < 0.05 has been marked with blue. Wilcoxon rank test p value < 0.05 has been marked with green.

	3 degrees	14 degrees	18 degrees	
Average pressure(N/cm2)	0.20±0.03	0.23±0.04	0.24±0.04	3-14,p<0.001, 3-18,p<0.001
Peak pressure(N/cm2)	0.62±0.15	0.79±0.30	0.89±0.29	3-14,p=0.001, 3-18,p<0.001
Contact area(cm2)	562.56±142.43	731.16±168.27	805.49±186.56	3-14,p<0.001, 3-18,p<0.001, 14-18,p<0.001

Table 2
Average pressure, peak pressure and contact area on the seat pan in three settings. Wilcoxon rank test p value < 0.05 has been marked with green.

	3 degrees	14 degrees	18 degrees	
Average pressure(N/cm2)	0.46±0.06	0.42±0.04	0.40±0.03	3-14,p<0.001, 3-18,p<0.001, 14-18,p=0.01
Peak pressure(N/cm2)	1.40±0.35	1.23±0.26	1.13±0.31	3-14,p<0.001, 3-18,p<0.001, 14-18,p=0.027
Contact area(cm2)	1077.27±169.19	1116.13±151.10	1136.97±135.36	3-18,p=0.024

Table 3
Total forces given by the backrest and the seat pan in three settings (unit = N).

	3°	14°	18°
Backrest	114.77 ± 9.83	169.54 ± 20.55	191.00 ± 29.40
Seat pan	501.84 ± 97.56	469.65 ± 74.05	458.47 ± 58.06

found between comfort and RMSSD, SDSD and HF with values of 0.231, 0.231 and 0.235, respectively. No significant correlations were found between discomfort and HRV features.

Table 4
The contribution of forces given by the backrest, the seat pan and the floor to hold the subject on vertical direction.

	3°	14°	18°
Backrest	5.44%	12.55%	15.83%
Seat pan	77.20%	69.61%	66.83%
Floor	17.36%	17.83%	17.34%

Table 5
COP moving speed in three settings (unit = cm/s). Wilcoxon rank test p value < 0.05 has been marked with green.

	3 degrees	14 degrees	18 degrees	
Backrest	0.59±0.21	0.51±0.21	0.51±0.18	3-14,p=0.048
Seat pan	0.31±0.42	0.23±0.1	0.27±0.11	3-18, p=0.004, 14-18,p=0.001

Table 6
HRV features in three settings with Wilcoxon rank test p < 0.05 marked with green.

	3 degrees	14 degrees	18 degrees	
SDNN	63.25 ±17.05	65.22 ±20.83	63.82 ±18.87	
RMSSD	48.42±13.00	48.10 ±15.10	48.95 ±14.20	
SDSD	48.42±13.00	48.10 ±15.10	48.95 ±14.20	
LF	1341.65±894.07	1175.93±871.10	1154.40±959.63	3-18,p=0.043
HF	664.98±472.42	686.71±494.09	708.56±588.97	
LF/HF	2.14 ±0.65	1.86 ±0.62	1.86 ±0.90	3-14,p=0.02,3-18,p=0.028

Table 7
Correlations between HRV features and comfort and discomfort with Pearson correlation p value < 0.05 marked.

	SDNN	RMSSD	SDSD	LF	HF	LF/HF
Comfort	0.143	0.231(p = 0.042)	0.231(p = 0.042)	0.197	0.235(p = 0.038)	−0.119
discomfort	−0.091	−0.155	−0.155	−0.161	−0.135	0.029

4. Discussion

4.1. Climbing angles

No significant differences in perceived comfort were found between the 3-degree and 14-degree settings. The perceived comfort is significantly lower than the 3-degree setting when the inclination angle is 18°. This might indicate that 18° should be avoided as the comfort of sitting in the 14-degree configuration is closer to the cruising stage which the inclination angle is 3°.

Udomboonyanupap et al. (2021) did a research focusing on comfort experience of using smart phones in beds with different inclination angles and found that angles that are too small or too large are not helpful in improving comfort experience. In our study, 14-degree configuration had a better performance than 18-degree configuration. This can be an indication of a possible inflection point on comfort between 14 and 18°. According to Ping (2021), most complains sitting in inclined aircraft seats were at the neck and the lower back area. As the inclination angle increases, the force on the seat shifts to the upper body. However, the fixed backrest angle (105°) might not be optimal for supporting passengers. Kilincsoy et al. (2014) indicated that 119° between upper leg and back are preferred by passengers sitting in car seat. Smulders et al. (2016) concluded that 121° are the preferred angle for passive relaxing sitting with the seat pan slightly reclines. Groenesteijn (2015) also found that 124° are the optimal backrest angle for reading in office chair. Though the scenarios differ, all backrest angles are larger than 105° and the seat pan is less tilted backward than in our study.

In this study it is shown that the discomfort increases and comfort decreases over time which is in accordance with previous studies (Sammonds et al., 2017)(Smulders et al., 2017). The values of comfort after 20 min are rather low compared with the literature. For instance, Anjani et al. (2021) showed that these values lower than 6 are comparable with seats smaller than 17 inch wide and a pitch lower than 30 inch. At the 18-degree setting the values were already lower than 6 after 10 min.

4.2. Pressure

Compared with the 14-degrees setting, significantly less mean pressure and peak pressure on the seat pan were shown in the 18° setting. Previous studies indicated that mean pressure and peak pressures are negatively correlated to perceived comfort (Li et al., 2020)(Noro et al., 2012). However, the perceived comfort of subjects in the 18-degree setting was not better than the 14-degree setting in this study. This can be a result of higher force on the backrest. Although the contact area was larger when the inclination angle increased, the fixed backrest angle led to a non-uniform distributions of the force, where pressures were concentrated at the buttock and the shoulder areas. This might be the reason of the lowered comfort score in the 18-degree setting (Bao et al., 2021). Meanwhile, the position of the gravitational center was moved towards the posterior direction with the increases of the angles, this might restrict movement as well (Kim et al., 2014). The COP movements on the seat pan in the 18-degree setting was significantly faster than the 14-degree setting. This can be a reflection of more posture changes and more discomfort (Furugori et al., 2003). However, no significant difference regarding discomfort were found between the two settings. It might be that 20 min is too short for the development of discomfort (Sammonds et al., 2017).

4.3. Compensatory movements

Table 4 shows that, the largest support force is always found at the seat pan. However, the COP moving speed at the backrest was always higher than that at the seat pan (Table 5). Compared with the buttock and the thigh area, it is easier for a subject to move his/her trunk due to the lower contact force between his/her upper body and the back rest. The movements of upper body could be the compensatory of discomfort of the buttock and thigh areas. According to Fujimaki and Noro (Fujimaki and Noro, 2005), macro movements always happen on the peak of discomfort and the discomfort drops rapidly after the movements. A few movements are expected during the period of discomfort development until the next discomfort peak value. Thus, body movements is an important indicator of participants for reducing discomfort, and humans tend to move in the easiest manner. Previous work confirmed that environments with enough space for movements is important to experience more comfort and less discomfort (Anjani et al., 2020). While flying passengers are required to sit most of the time during the flight, increasing the possibility of upper body to move might be helpful for them to reduce discomfort.

4.4. HRV

In this study, some HRV features were correlated to comfort. As '*comfort is seen as a pleasant state or relaxed feeling of a human being in reaction to its environment*'(Vink and Hallbeck, 2012) the correlation can be clarified. The mental status and the psychological stress can influence comfort directly. This is in accordance with literature as SDSD is considered to be the best HRV feature in showing the difference in the Trier Social Stress Test (TSST) measured by the mood questionnaire (MDBF) and progressive muscle relaxation (PMR) (Sghir et al., 2012) (Chen et al., 2020). Trends in RMSSD can show significant differences in different stress levels (Castaldo et al., 2015). Significant changes of HF was also found regarding stress levels (Castaldo et al., 2015). However, no correlation between HRV features and discomfort was found in this study. In the study requiring 2-h sitting period, correlations were found between discomfort and multiple HRV features including SDNN, LF, HF and non-linear parameters (Anjani, 2021). Since HRV is a sensitive indicator reflecting central–peripheral neural feedback and CNS (central nervous system)–ANS (autonomic nervous system) integration (Thayer et al., 2009), short term discomfort may not be reflected very well in a stable calm state. Perhaps it is more important that the heart does not have to work that hard in a more horizontal posture as the vertical distance to the head is shorter, therefore the required blood pressure is lower as well. Another explanation might be that discomfort is more related to physical factors (De Looze et al., 2003) and less to emotions and therefore less to HRV features. Comfort might be more related to emotions and thereby to HRV features.

4.5. Discomfort triggered adjustment

The experiment results indicated that discomfort triggered body movements, however, those movements are constrained by the interactions among the human, the product, the task and the environment, e.g. the gravitation direction. These discomfort triggered adjustments highlight the instinct of human on searching for comfort, in both/either a conscious and/or a subconscious manner. We describe this process as Discomfort Triggered Adjustment (DTA; see Fig. 6) as a supplement to the comfort model proposed by Vink and Hallbeck (2012) and later further detailed by Naddeo et al. (2014).

The DTA describes the process that when discomfort is experienced, it is a trigger for subjects to adjust the situation or adjust the human body to reduce the discomfort. Whether this adjustment is successful in reducing the discomfort depends on the possibilities and the effect. When the adjustment failed, this is again a trigger to change the environment, the product and/or the human body. Often humans move their body for different postures in seeking for comfort. If this is perceived as successful, the level of discomfort is acceptable and the cycle stops. After some time discomfort might develop again, triggering a new cycle. Only if the environment allows this to happen, the adjustment can be successful and the discomfort is reduced after the adjustment. Otherwise, the subjects fails to make the adjustment and the discomfort remains.

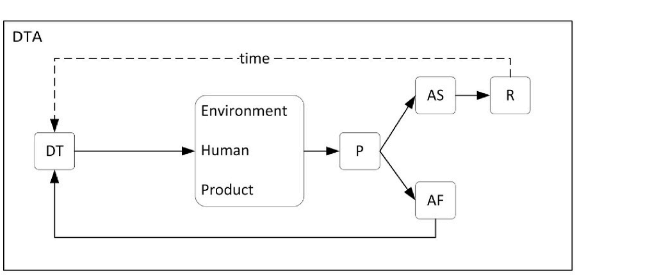

Fig. 6. DTA process in explaining the relation between discomfort, movement and the environment.

In the settings of this study, the inclination angle was the variable in the environment that changes the intensity of movements and interactions. With an inclination angle of 3°, subjects could easily have the discomfort reduced through movements. In the setting with the inclination angle of 18°, subjects kept moving, but were restricted during moving by safety belts and the changed gravitational force direction. Furugori et al. (2003) reported an increase in COP movements over time, which is probably more difficult in the reclined position with the result of an increase in discomfort. This loop is assumed to happen less in the setting with the inclination angle of 14° since the movement was the slowest.

The DTA process has links to the Fogg Behavior Model (Fogg, 2009). According to the Fogg Behavior Model, motivation, ability and prompt are the three necessary elements for behavior to occur. In the case of comfort and discomfort, motivation comes from the trigger caused by the discomfort. The higher level of the discomfort a subject is experiencing, the stronger the motivation is to adjust. The ability does not only depend on the subject but also on the product and the environment, especially for an environment with strict rules like aircraft cabins. When the inclination angle of the aircraft is large, the upright backrest and the safety belt make the postural adjustments in aircraft seats more limited, therefore the subjects will probably continuously seek for successful adjustments.

4.6. Limitations

The experiment was intended to simulate the climbing stage to study the influence of climbing angles on passengers' perceived comfort and discomfort. However, with a simulator on the ground, only the inclination angles were changed. Although the environment was set up in a real Boeing 737 cabin to give immersive experience, pressure changes, noise, acceleration and vibration in different conditions were not simulated and they do have influence on comfort (Vink et al., 2022). The age of the participants in this experiment were between 20 years and 30 years. Young children and senior groups might have different perceptions towards different climbing angles.

5. Conclusion

In this study, effects of different seat inclination angles on passengers' perceived comfort and discomfort were investigated. Subjective and objective measurement results on comfort and discomfort in 3 different settings indicated that 14° climbing angles might be preferable by passengers compared with 18°. Although no significant difference regarding (dis)comfort ratings were found between the 14° and the 18° settings, the perceived comfort and discomfort in the 14-degree setting were closer to the cruising angle setting (3°). The 18° discomfort is significantly higher compared with the 3°, indicating that it should be avoided. The COP moving speed, indicating the movements, of both the backrest and the seat pan in the 14-degree were the smallest of the three settings. The results also show that the COP moving speed on the backrest was always higher than the seat pan. The high COP moving speed on upper body could be the indication of compensatory movements since the movements of buttock and thigh areas were limited by the force and the seat belt. The results could be explained by embedding a Discomfort Triggered Adjustment (DTA) process in existing comfort models to address the cycle of the development of discomfort, the trigger, the friction between the wish of the movements and the practical constraints until the joy of comfort.

Author statement

Xinhe Yao: Conceptualization, Methodology, Investigation, Formal analysis, Writing - Original Draft, Yayu Ping: Methodology, Investigation, Writing - Original Draft, Yu (Wolf) Song: Conceptualization, Writing - Review & Editing, Supervision, Peter Vink: Writing - Review & Editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Xinhe Yao reports a relationship with Delft University of Technology that includes: non-financial support. Yayu Ping reports a relationship with Delft University of Technology that includes: non-financial support. Yu Song reports a relationship with Delft University of Technology that includes: employment. Peter Vink reports a relationship with Delft University of Technology that includes: employment. Xinhe Yao reports a relationship with China Scholarship Council that includes: funding grants. Xinhe Yao reports a relationship with Horizon Europe that includes: funding grants. Yayu Ping reports a relationship with Horizon Europe that includes: funding grants. Yu Song reports a relationship with Horizon Europe that includes: funding grants. Peter Vink reports a relationship with Horizon Europe that includes: funding grants.

Data availability

The authors do not have permission to share data.

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