Comfort Experience in Air Travel

Research Methods and Design

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Comfort Experience in Air Travel:
Research Methods and Design

Dissertation

for the purpose of obtaining the degree of doctor

at Delft University of Technology

by the authority of the Rector Magnificus Prof.dr.ir. T.H.J.J. van der Hagen

Chair of the Board for Doctorates

to be defended publicly on

Monday 2, October 2023 at 15:00 o'clock

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Summary

Comfort, which is defined as "*a pleasant state or relaxed feeling of a human being in reaction to its environment"*, plays an important role in air travel both for passengers and airlines. However, the combination of strict safety regulations, limited space, and a large variation in passenger body types make aircraft cabins challenging environments to create comfort. The studies presented in this PhD thesis focus on different aspects of comfort experience in air travel and are aimed to be helpful for aircraft interior designers, as well as airlines to have creative design solutions for inflight comfort issues in the future.

Factors influencing comfort and discomfort are discussed in this thesis (Chapter 2). The first experiment was conducted in a Boeing 737 fuselage and essential oils were used to produce different scents in the cabin. 276 participants were divided into 9 groups and exposed to different scents for 60 minutes. Questionnaires were used before and after the experiment to measure the effect of the scent on (dis)comfort. In terms of perceived comfort, mandarin scents outperformed lavender and cedar scents. On the same day, the comfort levels of those exposed to mandarin scents were significantly higher compared to the control group. However, the effects of scents tended to diminish over time, as after 60 minutes, there were no significant differences observed between the different scent groups and the control group.

The second experiment in Chapter 2 was a within-subject study that compared comfort levels during climbing in different inclination angles. Twenty-six participants were asked to experience three inclination angles of 3, 14, and 18 degrees in a Boeing 737 cabin for 20 minutes each. The perceived (dis)comfort, heart rate variability, and pressure on the backrest and seat pan were recorded using questionnaires, HRV bands, and pressure mats, respectively. The outcomes showed that climbing with an inclination angle of 14 degree might be beneficial. The study also showed that HRV recordings are difficult to clearly link to comfort, while the pressure distribution data are easier to understand.

Measurement of perceived (dis)comfort is discussed in Chapter 3. Two studies that aim to establish relationships between (dis)comfort and objective data are presented. The first study explored the relationship between pressure features and (dis)comfort of users in aircraft seats using a newly proposed 6-division method on the pressure maps. With the proposed division method, the location of the crotch point is used to divide buttock and thigh, as well as the left and right side, another horizontal line is used to split thigh area equally into proximal and distal posterior thigh. Thirty-three subjects participated in the experiment and completed comfort questionnaires while sitting on each cushion in 4 postures. Pressure data of the surface both on the top and bottom of three cushions with different stiffnesses were collected. The results demonstrated the benefits of utilizing the proposed division method and highlighted the importance of gathering pressure features with consideration of human body structure.

In the second study of Chapter 3, a loose-fit wearable and a tight-fit version were designed with the same hardware and software to evaluate their ability to capture the right postures while wearing. Thirty-five participants evaluated their overall comfort/discomfort while performing 7 frequently observed in-flight postures while wearing each wearable in a Boeing 737 cabin. The study confirmed that loose-fit wearables are adequate for recognizing inflight sitting postures.

Additionally, the loose-fit wearable demonstrated significantly better performance regarding both comfort and discomfort.

A design application of comfort theories is introduced in Chapter 4. An aircraft seat design that uses vertical space in the cabin, “chaise longue” , was designed. To test whether passengers perceive advantages and experience differences in (dis)comfort, 29 participants were asked to sit for 40 minutes in the new seat and a traditional aircraft seat. Comfort scores were recorded every 10 minutes, and interviews regarding comfort experience were conducted after the tests. A majority of the participants (76%) indicated a preference for the “chaise longue” seat due to its advantages in reclined sitting, sleeping, and watching in-flight entertainment device. Many individuals recognized the potential of the “chaise longue” design to offer a more spacious and comfortable experience. However, the low-fidelity of the prototype for the new seats did not show significant differences in comfort and discomfort, showing challenges for the use of low fidelity prototypes in validating (dis)comfort.

In Chapter 5, a general discussion and recommendations for future research were made. The patterns of the development of (dis)comfort under different circumstances over time should be studied further. Both subjective and objective measurements are helpful in building relationships between (dis)comfort and body changes in a controlled environment.

In order to comprehend different aspects of (dis)comfort, participatory empirical research was carried out in this PhD, encompassing both subjective and objective measurements to establish correlations. The research process included planning, acting, evaluating, and reflecting in each study. The objective was to investigate the factors of comfort, measure comfort levels, and employ relevant theories to enhance the design process, ultimately improving the passengers' comfort experience. This PhD thesis attempts to expand the scope of comfort theories and their practical application in design.

Samenvatting

Comfort, dat wordt gedefinieerd als "een aangename toestand of ontspannen gevoel van een mens als reactie op zijn omgeving", speelt een belangrijke rol in luchtvaart voor zowel passagiers als luchtvaartmaatschappijen. De combinatie van strikte veiligheidsvoorschriften, beperkte ruimte en een grote variatie aan lichaamstypes van passagiers maken het creëren van comfortabele vliegtuigcabines echter uitdagend. De studies gepresenteerd in dit proefschrift richten zich op verschillende aspecten van de comfortbeleving tijdens vliegen en zijn bedoeld om behulpzaam te zijn voor vliegtuiginterieurontwerpers en luchtvaartmaatschappijen bij het vinden van creatieve ontwerpoplossingen voor toekomstige comfortproblemen.

Dit proefschrift gaat over verschillende factoren die comfort en ongemak beïnvloeden (hoofdstuk 2). Het eerste experiment werd uitgevoerd in een Boeing 737 romp en essentiële oliën werden gebruikt om de cabine verschillende geuren te geven. 276 deelnemers werden verdeeld in 9 groepen en werden gedurende 60 minuten blootgesteld aan de verschillende geuren. Vragenlijsten werden voor en na het experiment gebruikt om het effect van de geur op (on)comfort te bepalen. Wat betreft het waargenomen comfort, presteerden mandarijngeuren beter dan lavendel- en cedergeuren. Aan het begin waren de comfortniveaus bij mandarijngeuren significant hoger in vergelijking met de controlegroep. De effecten van geuren namen echter af na verloop van tijd. Na 60 minuten waren er geen significante verschillen meer tussen de verschillende geurgroepen en de controlegroep.

In het tweede experiment in hoofdstuk 2 werden comfortniveaus vergeleken tijdens het stijgen van het vliegtuig in verschillende hellinghoeken. Zesentwintig deelnemers werden gevraagd om te zitten in hellinghoeken van 3, 14 en 18 graden in een Boeing 737-cabine gedurende 20 minuten. Het waargenomen (dis)comfort, de hartslagvariabiliteit en de druk op de rugleuning en zitting werden geregistreerd met behulp van vragenlijsten, HRV-banden en drukmatten. De resultaten toonden aan dat klimmen met een hellinghoek van 14 graden te prefereren is. De studie toonde ook aan dat HRV-registraties moeilijk zijn te linken n comfort, terwijl de drukverdelingsgegevens een duidelijker relatie hebben .

In hoofdstuk 3 staan twee onderzoeken die tot doel hebben om relaties tussen (on)comfort en objectieve gegevens vast te stellen. Het eerste onderzoek onderzocht de relatie tussen drukverdeling en (dis)comfort van gebruikers in vliegtuigstoelen met behulp van een nieuw voorgestelde indeling in 6 gebieden. Met de voorgestelde indeling wordt het kruispunt tussen billen en dij gebruikt om bil en been te scheiden, De verdeling tussen linker- en rechterzijde van het lichaam wordt gebruikt en , een andere horizontale lijn wordt gebruikt om het dijbeenoppervlak gelijkmatig in een proximaal en distaal deel te verdelen. Drieëndertig proefpersonen namen deel aan het experiment en vulden comfortvragenlijsten in terwijl ze op elk kussen in 4 houdingen zaten. Drukgegevens van het oppervlak zowel op de boven- als onderkant van drie kussens met verschillende stijfheden werden verzameld. De resultaten toonden de voordelen aan van het gebruik van de voorgestelde indeling en benadrukten het belang van het verzamelen van verschillende drukeenheden.

In het tweede deel van Hoofdstuk 3 werd een losse en strakke draagbare jasje ontworpen met dezelfde hardware en software om houdingen tijdens het dragen te kunnen bepalen. Vijfendertig deelnemers evalueerden hun algehele comfort en ongemak met het jasje terwijl ze 7 vaak

waargenomen in-flight houdingen aannamen . Het onderzoek bevestigde dat losse draagbare jasjes geschikt zijn voor het herkennen van in-flight zithoudingen. Daarnaast vertoonde het losse jasje significant betere prestaties voor zowel comfort als ongemak.

In hoofdstuk 4 is een vliegtuigstoel ontworpen die verticale ruimte in de cabine gebruikt: de "chaise longue". Om te testen of passagiers voordelen ervaren en er verschillen in (dis)comfort werden ervaren, werden 29 deelnemers gevraagd om 40 minuten in de nieuwe stoel en in een traditionele vliegtuigstoel te zitten. Comfortscores werden elke 10 minuten geregistreerd, en interviews over de comfortervaring werden na de tests afgenomen. Een meerderheid van de deelnemers (76%) gaf de voorkeur aan de "chaise longue" -stoel vanwege het ruime achterover leunen, de mogelijkheid van slapen met de benen gestrekt en het beter kunnen kijken naar in-flight entertainment. Veel mensen erkenden de potentie van het "chaise longue" -ontwerp om meer bewegingsruime te bieden aan de passagier. Het feit dat het prototype een spuugmodel was zorgde ervoor dat er geen significante verschillen in comfort en ongemak werden gevonden, wat de uitdaging laat zien bij het gebruiken van prototypes met een lage kwaliteit voor het bepalen van het (dis)comfort.

Het laatste hoofdstuk (hoofdstuk 5) bevat een discussie over alle experimenten en aanbevelingen voor toekomstig onderzoek. Het is van belang het comfort proces te bestuderen onder verschillende omstandigheden in de loop van de tijd, omdat het comfort aan begin anders kan zijn dan aan het eind. Zowel subjectieve als objectieve metingen zijn nuttig bij het leggen van verbanden tussen (on)comfort en veranderingen in het lichaam in een gecontroleerde omgeving.

Om verschillende aspecten van (on)comfort te begrijpen, werd participatief empirisch onderzoek uitgevoerd in deze PhD. Het omvatte zowel subjectieve als objectieve metingen, waartussen correlaties werden vastgesteld. Het onderzoeksproces omvatte plannen, uitvoeren, evalueren en reflecteren op ieder onderzoek. Het doel was om de factoren die comfort beinvloeden te onderzoeken, comfortniveaus te meten en relevante theorieën toe te passen om het ontwerpproces te verbeteren, om uiteindelijk de comfortervaring van passagiers te verbeteren.

Reading guide and nomenclature

ANS	Autonomic Nervous System
AVC	Absolute value of correlation
B	Buttock region
BL	Buttock left region
BMI	Body Mass Index
BR	Buttock right region
CA	Contact area
CAD	Computer-aided design
CNS	Central nervous system
COP	Center of pressure
CV	Coefficient of variation
D	Distal posterior thigh region
DCNN	Deep Convolutional Neural Network
DL	Distal posterior thigh left region
DNN	Deep Neural Network
DR	Distal posterior thigh right region
ECG	Electrocardiogram
HF	High frequency of the heart rate
HREC	Human Research Ethical Committee
HRV	Heart Rate Variability
IFE	Inflight entertainment
IMU	Inertial Measurement Unit
LF	Low frequency of the heart rate
LF/HF	Ratio of LF and HF
LPD	Local Postural Discomfort
MDBF	Mood questionnaire

MLP	Multilayer perceptron
P	Perceived changes
P	Proximal posterior thigh region
PC	Principal component(s)
PL	Proximal posterior thigh left region
PMR	Progressive Muscle Relaxation
PR	Proximal posterior thigh right region
RMSSD	Root mean square of successive n-n interval differences
SDNN	Standard deviation of the time interval between successive normal heart beats
SDSD	Standard deviation of differences between adjacent n-n intervals
SHAP	SHapley Additive exPlanations
SPD%	Seat pressure distribution percentage
SVM	Support Vector Machine
T	Thigh region
TL	Thigh left region
TR	Thigh right region
TSST	Trier Social Stress Test
VA	variance
VOC	volatile organic compound
WHO	World Health Organization

1. Introduction

Comfort in air industry

Aircrafts have been used for long-distance transportation since the early 20th century. Airplanes of different types and sizes were designed and manufactured to accommodate the rapidly increasing number of passengers. As a fast and safe way of transportation, air travel became the preferred choice for those taking longer trips. The air traffic industry has been growing with a rapid speed and such increment will continue in the near future [1,2]. As a result, offering a comfortable experience during the flight is becoming more and more important for both passengers and airline companies.

Aircraft cabins represent uniquely challenging environments for human factor issues through the stringent safety regulations next to the volume constraints and a wide variety of body types of travelers. When booking a flight, passengers seek comfort and are willing to pay higher prices in exchange for increased seat comfort [3,4] or select between two flights with the same price the most comfortable one [5]. A pleasant and comfortable experience also increases the likelihood that customers will return to an airline for future travel [6]. For regional aircrafts, passengers frequently name the cabin environment as the most important factor in their choice of an airline, and there is a strong correlation (r=0.73) between aircraft interior comfort and “fly again with the same airline” [7]. Improving the comfort and perception of space and environment is at the heart of these challenges. One of the main factors influencing comfort in the airplane is the seat [8].

Zhang et al. [9] identified comfort and discomfort while seated and found influencing factors. Comfort relates to a feeling of well-being and discomfort to physical factors. Later the definition of comfort has been refined as “*a pleasant state or relaxed feeling of a human being in reaction to its environment”* by Vink and Hallbeck [10] and discomfort has been defined as “*an unpleasant state of a human being in reaction to its physical environment*”.

Comfort model

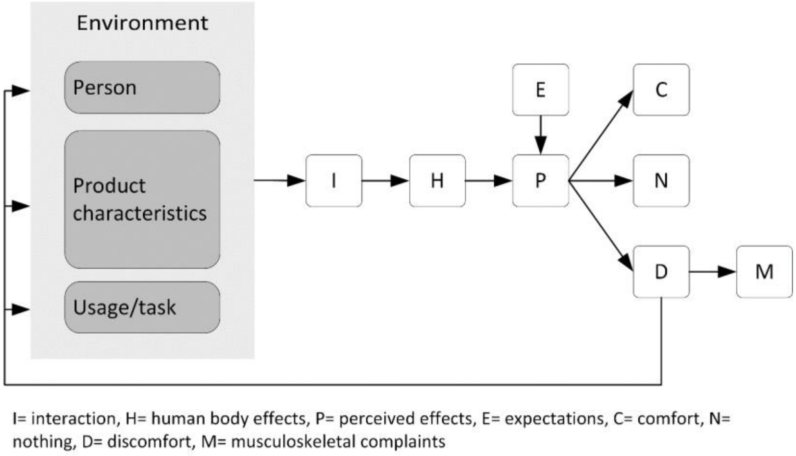


Figure 1.1 Theoretical model developed by Vink and Hallbeck (courtesy of Vink and Hallbeck, 2012)

To understand how the perceptions towards comfort and discomfort are formed, researchers established different conceptual models. Vink and Hallbeck presented a comfort model (Figure 1.1) in 2012. Given a task, a passenger may have a certain expectation of the comfort. Meanwhile, the interaction between the passenger and the product (e.g. seat), other passengers (e.g. neighbours, flight attendant) and the environment (e.g. air quality, temperature, vibrations, etc.) will create certain human body effects, like postural and physiological aspects. Passengers may conduct unconscious movements to deal with these phenomena, and these will develop a perception and emotion of the situation at this moment. Balancing with their expectation, this will create a feel of comfort or discomfort.

Comfort factors

Under the 'coating' of comfort, different factors work together to make the overall experience acceptable [11]. According to the model shown in Figure 1.1, stimuli from the environment, person(s), products, and tasks combine to create interactions and unique experiences for each individual. Anthropometry, climate, noise, vibration, visual, smell and air quality in the environment are highlighted factors in past studies [12,13]. Vink et al. [14]conducted a study in turboprop with 97 passengers during the flight and found that space is the most important factor regarding comfort and noise is the most influential factor of discomfort (Figure 1.2 & 1.3). Besides the stimuli of the environment, personal life experience as well as individual differences in the physical and mental state of a human being play a role. An example of individual differences is the influence of fat. The distribution and amount of subcutaneous body fat at different body sites can cause different reactions of passengers towards pressure pain and thermal stimuli [15,16], which could have influence on discomfort perception. Personal health status also matters. Physiological dysregulations, states and illnesses could potentially lead to alterations in perceptions of comfort and discomfort. The ability of producing Serotonin (5-HT) directly influences the behavioral responses to stimuli in the environment and emotion regulation [17,18]. People with less healthy thyroid may therefore experience more fatigue, muscle weakness and anxiety [19], which could influence comfort perception as well. However, specific manifestations of different individuals vary a lot. Other people in the neighborhood also matter. It was mentioned in previous work that flight attendants with warm smiles could increase passenger comfort and scrambling for the armrest may harm the comfort experience [5]. The indirect interactions between people could also influence passengers well-being. It was found that the presence of others in close proximity appears to heighten stress levels and worsen responses to air quality [20].

Products and their features influence comfort and discomfort as well by influencing the way interactions between products and the human will proceed during the performance of different tasks. The aircraft seat, as the product with most interaction in the cabin, can make a significant impact on aircraft cabin comfort [21]. The support characteristics of the seat determines the body postures during travelling and thereby influences the perceived comfort [22]. Reduced seat pitches and the sharp edges of the seat in an aircraft cabin can increase the complaints of passengers [5]. Textile upholstery of the seat can also influence the skin sensory comfort through mechanical sensation at the body parts with direct contact of a product [23]. Apart from the seat the tray table on the back of the seat might influence the passengers comfort as well. In some activities like eating it determines the neck posture when using the tray table. The height of the tray table was suggested to be 78±2cm to provide a comfortable experience in economy class cabin [21].

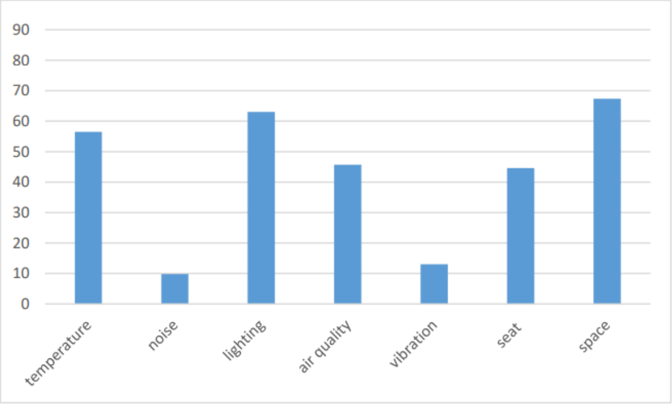


Figure 1.2 Percentage of passengers that report factors influencing comfort (courtesy of Vink et al., 2022)

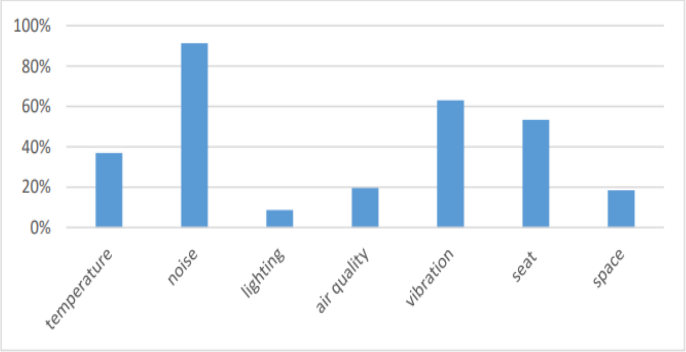


Figure 1.3 Percentage of passengers that report factors influencing discomfort (courtesy of Vink et al., 2022)

Comfort measurements

Due to the fact that comfort is a personal feeling, subjective measurements, which are usually done with questionnaires, are still the “golden standard” of measuring comfort and discomfort [24]. The questionnaire used most in later chapters of this thesis is the overall comfort and discomfort questionnaire, which is also known as the simple comfort score questionnaire. The questionnaire only contains two questions to ask about overall comfort and discomfort [6] [25]. Anjani et al. conducted a study including 55 researchers working in relevant areas and confirmed the advantage of using this questionnaire in an early design phase and end product evaluation for the concision and effectiveness [26].

Besides subjective measurements, objective measurements are also used to measure environment factors, human body shapes, interaction and human body effects (physiological parameters). The use of different measurement can be found in Figure 1.4. Temperature [27,28], humidity [29,30], air velocity [31,32], CO_2 concentration [33,34], vibration [35,36], and noise [37,38] are the common parameters to describe the environment features. Anthropometry [39], posture/movement [40,41], pressure/force [42,43] and foot volume change [44] can be measured for the physical interaction process. Physiological parameters such as skin temperature [45,46], pulse rate [47], HRV (heart rate variability)[26,48], GSR (Galvanic Skin Response) [24], EMG (Electromyography) [49], eye movements [50,51] can be measured to study human body effects. Depending on different contexts and scenarios, the selection of the objective measurements and device can vary a lot in comfort studies.

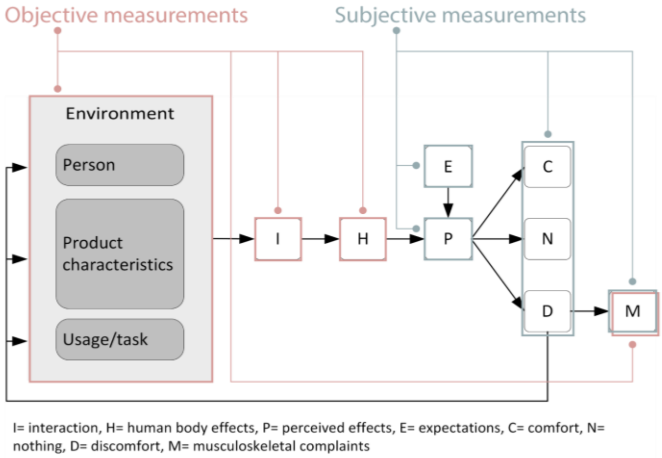


Figure 1.4 Measurements in different parts of comfort model developed by Vink and Hallbeck (2012)

The gap

Since comfort is based on human feelings, anything in the environment that could be sensed by people could make differences. Many factors influencing comfort in different contexts were studied in previous researches. However, some factors are still not fully researched, especially with considerations of the context in aircraft cabin. For instance, scent in aircraft cabin is not often studied. In addition, there is not much knowledge how comfort is perceived in the take-off and climbing phase of the aircraft. At the same time, for a better understanding and prediction of comfort and discomfort, building the relationship between objective data and perceived (dis)comfort might be helpful. Although studies have been done regarding different factors and measurements, there are still many unknown phenomena in the field due to the wide range of influencing factors, different ways of measurement and complexity of varying contexts. Achieving more knowledge in this field could help designers to gain understanding towards human needs in different contexts and with different tasks. It is worth exploring this, as it could give indications for how and what to measure. Furthermore, this exploration could provide valuable input for comfort theories in human-centered design, ultimately enhancing the overall experience.

In the field of sitting comfort the most used objective recording system related to discomfort is the pressure mat. There are some guidelines on the ideal pressure distribution (e.g. [43]). It was also suggested that the ideal pressure distribution leads to lowest load on the discs [52]. However, the way the seat pan is divided in these recordings is open for discussion. This PhD thesis tries to shine some light on this topic.

Much research on the aircraft cabin focuses on the cruise flight (e.g. [39]). However, an airplane has a take-off and climbing phase and landing phase as well. The position in the climbing phase is completely different and the comfort is therefore studied in this thesis. In addition, it might be interesting to see whether we can predict the posture based on data as this might be applied in future research studying posture variation, which is relevant in reducing discomfort. Lastly, for sustainability and economic reasons, it might be beneficial to accommodate more passengers on the airplane while ensuring even greater comfort. The vertical space in aircrafts is underused and a potential innovation using vertical space has been studied as well.

Research focus and approach

This project aims at exploring the factors influencing (dis)comfort and the relations between different factors and perceived (dis)comfort, especially in an aircraft cabin, to improve the comfort experience during travel. The research focus leads to the overarching research question:

What should be researched regarding comfort to improve the aircraft interior design for a better comfort experience?

The scope of this research incorporates two topics: comfort, and design. It is impossible to study all aspects, therefore the research objective is focused on three research questions and multiple sub research questions. This thesis is structured according these research questions. The approach in relation to these research questions can be found in Figure 1.5.

1. Based on the fact that there is no literature yet in these fields, two areas regarding factors influencing perceived (dis)comfort in the aircraft cabin are explored:
    1.1 What are the effects of different scents on perceived (dis)comfort of aircraft passengers?
    1.2 What are the effects of different inclination angles on comfort/discomfort experience of passengers during the climbing phases of a flight?
2. How to build the relationships between (dis)comfort in aircraft cabin and objective data collected in experiment?
    2.1 Which pressure map measures (including the division of pressure of the contact area) are more suitable for evaluating the comfort/discomfort experience of passengers and can the relationships between comfort/discomfort and the pressure map be captured under the cushion?
    2.2 Is it possible to recognize inflight sitting postures with loose-fit wearables and how do the loose-fit wearable perform regarding comfort and discomfort compared to the tight-fit wearable?
3. How to improve the comfort experience of air passengers by offering a better aircraft interior design?

3.1 Is the seat design 'chaise longue' using the vertical space in a new way preferred above a traditional aircraft seat positioned at 32" pitch and could the comfort experience of passengers be improved with the new design?

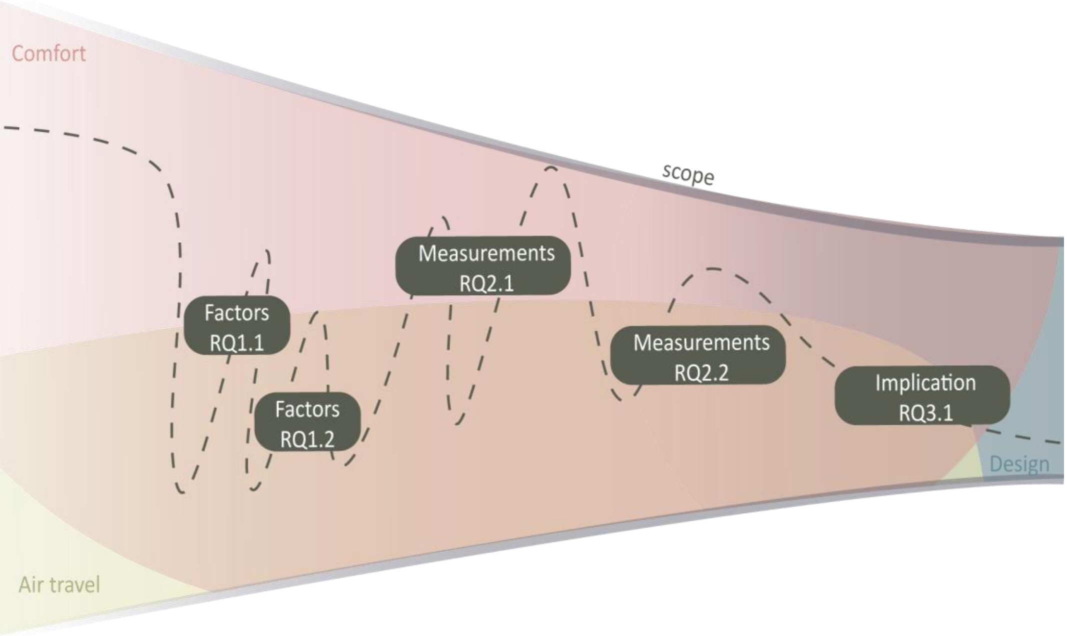


Figure 1.5 The research approach in relation to the research questions

Thesis outline

The structure of this thesis can be found in Figure 1.6. It follows the aforementioned research questions and is divided into 5 chapters.

Chapter 1 gives an overview of the thesis. Background and framework of the research are introduced.

Chapter 2 explores two factors that may influence the perceived (dis)comfort. With different essential oils used in a Boeing 737 fuselage, the effects of different scents on perceived (dis)comfort of aircraft passengers was studied. 276 participants were divided in 9 groups and exposed to different scents for 60 minutes. The effect of the scents was measured by a set of questionnaires at the beginning and at the end of the experiment, respectively.

The second research was a within-subject experiment comparing the comfort experience during climbing with different inclination angles. Twenty-six participants were invited to experience three inclination angles including 3, 14 and 18 degrees in a Boeing 737 cabin. Participants experienced each setting for 20 minutes 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.

Chapter 3 presents two studies focusing on building relationships between (dis)comfort and objective data. In the first study, the relationships between pressure maps and (dis)comfort of users in aircraft seats with the focus on a new 6-division method on the pressure maps collected at the bottom of the cushions were explored. 33 subjects joined the experiment and while sitting on each cushion in 4 postures, they completed comfort questionnaires. Pressure maps on the top as well as at the bottom of cushions were collected and analyzed. In the second study, a loose-fit wearable as well as a tight-fit version were designed with the same hardware and software. The performance regarding the capturing of the right postures while wearing were evaluated by 35 participants in a Boeing 737 cabin. During the experiment, the participants were asked to perform 7 frequently observed in-flight postures while wearing each wearable, and their overall comfort/discomfort were rated as well.

Chapter 4 introduces an aircraft seat design using the vertical space in cabin. To test whether passengers see the advantage and experience differences in (dis)comfort, 29 participants were asked to sit for 40 minutes in the new and in a traditional aircraft seat. The (dis)comfort scores were documented every 10 minutes. Interviews regarding comfort experience were taken after the tests.

Chapter 5 discusses the results of the studies and presents a conclusion.

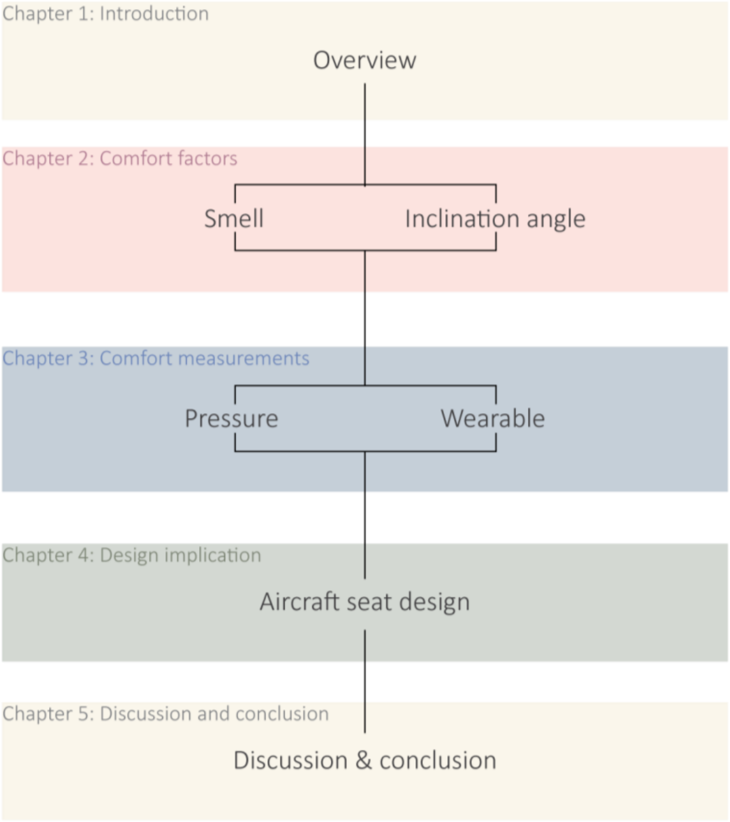


Figure 1.6 Thesis outline

2. Comfort factors

This chapter is based on following papers:

1. Yao X, Song Y, Vink P. Effect of scent on comfort of aircraft passengers. Work. 2021;68: S273–S280. doi:10.3233/WOR-208025
2. Yao X, Ping Y, Song Y (wolf), Vink P. Sitting comfort in an aircraft seat with different seat inclination angles. Int J Ind Ergon. 2023;96: 103470. doi:10.1016/J.ERGON.2023.103470

Effect of scent on comfort of aircraft passengers

Abstract

Background: Scents may influence the perceived comfort of an environment. There are only a few studies conducted on the relationship between scent and comfort in aircraft cabin.

Objective: The goal of this research is to explore whether relationships between scents and perceived comfort can be found for passengers in an aircraft cabin.

Methods: 276 participants joined an experiment in a Boeing 737 fuselage. The participants were divided into nine groups and each joined a session for 60 minutes with the exposure to different scents. The effect of the odor was measured by a set of questionnaires at the beginning and at the end of the session. Results of questionnaires were analyzed regarding the effects on the completion time, of the type of scents, of the intensity of the scent and on gender.

Results: Significant differences were found at the beginning and at the end of the experiment regarding comfort and emotion, but sometimes no relations could be established. The influence of different scents on comfort/discomfort varied and changed over time. However, in all scenarios, participants' scores on emotion decreased. Additionally, the added scents influenced the linearity between the changes in comfort and discomfort.

Conclusions: Smell could influence the perceived comfort/discomfort of aircraft passengers over time, and different types of smells have different effects on passengers. The preferences on scents are diverse, which highlights the need for personalization in aircraft cabin design.

Keywords: scents, comfort, discomfort, emotion, human perception

Introduction

Travelling by air has become more affordable and more popular [2], and offering a better comfort experience to passengers is interesting to airlines, as a correlation between comfort of the aircraft interior and "fly again with the same airline" has been established [39].

Vink and Hallbeck [10] defined comfort as: "*a pleasant state or relaxed feeling of a human being in reaction to its environment*". Therefore, comfort can be seen as an effect of physical stimuli and the physical, mental, emotional and social states of the subject over time. In the past decades, many studies have been conducted to explore different physical stimuli that may influence passenger comfort. For instance, Krist [12] and Bubb et al. [13] state that comfort was established through six factors: anthropometry, climate, sound, vibrations, light and smell for automotive passengers. Among those factors, smell was considered to be one of the basic influential aspects of the discomfort pyramid [53]. Bouwens et al. [39] also explored the importance of those factors for aircraft passengers and they ranked smell as the third most important factor regarding their experience on aircraft interior comfort. Additionally, they found that smell could influence people's experience unconsciously [54].

Smell is everywhere in the human daily life, and it is one of the ways to communicate with the surrounding environment, i.e. identifying species and detecting danger [55]. Different odor compounds are sensed by odor receptors located in the nose after exhalation and then processed by the brain. Meanwhile, odor compounds can also be absorbed through skin and influence brain neurotransmitter and hormone levels [56]. These signals are then communicated to higher cortex regions, which manages conscious thoughts process, before moving into the limbic system and producing sensational physical behavior [57].

Smell may influence the mental state of a subject. For instance, the stress biomarkers, dehydroepiandrosterone, oxidative stress, estradiol, dopamine, cutaneous barrier, sebum secretion and the cutaneous immune system of human are all influenced by olfactory function [58]. In folk medicine as well as in aromatherapy, essential oils and fragrance compounds are widely used as a solution for labor pain, chemotherapy side effects, rehabilitation of cardiac patients, restless sleep and post-surgical discomfort [59].

Smell may also change the emotional state of the subject by influencing mood, evoking powerful experiences of pleasure or displeasure, producing alertness or relaxation, and evoking long-forgotten emotional memories [60]. In 1986, Gibbons found that olfactory functions may be able to evoke particular memories and emotions in a more direct way than other senses [61]. Lieff and Alper [62] also described olfactory as “our most emotional sense”, which could be explained by the neural structure involved in odor signal processing, as the neuroanatomy of olfactory is intertwined with emotion processing regions in the brain [63].

Smell is also related to the social behavior of human beings. Research showed that natural body odor informs social judgments about health, gender, sexual orientation, and even individual identity [64]. People are more prosocial and willing to help others in the environment with pleasant ambient fragrance [65]. Trust can also be enhanced implicitly via undetected smells [66].

In short, smell may influence the perceived comfort by influencing the mental, emotional and social states of a subject. For instance, in the comfort model developed by De Looze et al. [67], emotion was mentioned as a factor with strong impact on comfort. Ahmadpour et al. [8] also identified the strong correlation between the state of emotion and the perceived comfort of passengers in aircraft. It is also believed that bad odors from a neighbor in a closed space, e.g. aircraft cabin, can cause a negative effect on the perceived comfort [5].

However, the relations between different scents and the perceived comfort/discomfort of air passengers over time are not fully explored. For instance, the ability to distinguish a particular odor after a prolonged exposure (olfactory fatigue) regarding comfort is not clear yet, as the limited space inside an aircraft cabin makes it difficult for odors to dissipate and it is unknown at which point humans get used to a scent after in an environment, thus cause olfactory fatigue [68]. The effects of different types of smells with different intensity on comfort are also not fully explored.

Materials & Methods

The aim of this study is to explore relationships between exposure to scents and the perceived comfort over time. The study was conducted in a Boeing 737 fuselage and was designed to be a between-subject experiment. A total of 276 university students (154 females, 93males, 29 not mentioned) were invited to participate in the study. The students were divided into nine groups, and each group joined a session which lasted around 60 minutes. These nine sessions were carried out during three days with three sessions per day. The first session of each day was used as a control group, i.e. the researchers did not add a scent in this session. From the second session, scents were introduced. Due to its wide usage in aromatherapy, the pure essential oil was selected to produce the smell [59]. In the second session of each day, 4 drops (about 0.05 ml/drop) of essential oils (brand: Holland & Barrett) were applied to each of three aromatherapy burners. These three identical burners were deployed in the front, the middle and the end of the fuselage cabin, respectively. In the third session of each day, 12 drops of essential oils were applied to double the perceived intensity of the smell. The number of drops was calculated based on Steven's power law [69], which describes the relation between the perceived changes (P) and the actual changes of physical stimulus (I) as $P = kI^a$. Here k is a constant and for smell, it was set as 0.6. After the third session, the session with the most intensive scent used, of each day, a forced air ventilation was utilized to disperse the residual smell to prepare the experiment for the following day. Three types of scents, lavender, cedar and mandarin were used each day during the three-day experiment. Everyday only one type of scent in different intensity was used. Table 2.1 lists the setups and the schedule of the experiment. The reason of choosing these three scents is that there are indications that these scents have the function of improving the mood by increasing the feeling of calm, relaxed and reducing stress [70].

Table 2.1 Experiment schedule

	1st day	**2nd day**	**3rd day**
Session 1	No scent added	No scent added	No scent added
15min break, participants group change			
Session 2	Lavender (4 drops) in each burner	Cedar (4 drops) in each burner	Mandarin (4 drops) in each burner
15min break, participants group change			
Session 3	Lavender (12 drops) in each burner	Cedar (12 drops) in each burner	Mandarin (12 drops) in each burner

The comfort/discomfort questionnaire [6] (11 point scale; 0 = no comfort/discomfort, 10 = extreme comfort/discomfort) and the PrEmo questionnaire [71] were used in this study to get an indication of the perceived comfort/discomfort and the emotion. PrEmo questionnaire is a non-verbal self-reported questionnaire contains in total fourteen emotions including seven positive emotions and seven negative emotions expressed by a cartoon character [71]. The division of emotions was also mentioned by Russell [72] that all the emotions can be placed in the scale of arousal(high-low) and valence(positive-negative). The procedure of each session was the same, in which the host researcher welcomed the participants and then acquired a signed informed consent form from each subject. The participants were then seated and completed a comfort/discomfort questionnaire and a PrEmo questionnaire. After filling in the questionnaires, participants were asked to sit and use their mobile phone. They could do the task they wanted (e.g. texting, reading, gaming). Every 10–15 minutes, they had a chance to walk in the cabin to avoid the occurrence of physical complaints on comfort and discomfort [73]. Each session took 60 minutes. At the end of the session, the participants were asked to complete the second set of questionnaires, which was the same as the first set. To avoid allergy, participants were informed of the scents prior to the experiment, so they can register themselves into control groups.

In the process of analyzing the data collected from the experiment, missing data (dependent on the question 11–18 out of 276 answers were missing) were excluded for the analysis. In the interpretation of the emotions in this study, the fourteen emotions were divided into two groups, either positive emotions or negative emotions according to Desmet and Wassink [74] . All negative emotions were assigned as -1 while the positive emotions were set as 1. Data sets were grouped regarding completion time, scents, intensity, time and genders. The normality of the data was then checked using the Shapiro-Wilk test [75] with and without log transformation. Since the distribution of data did not fit the normal distribution, the Mann-Whitney U test was selected to evaluate the dependence between data sets. Principal components analysis(PCA) [76] was conducted regarding the changes of comfort and discomfort. There were rainfalls with varied precipitation from time to time during the three days and the temperature on the three days were 17.5°C, 15°C and 17°C respectively while the humidity were 94%, 80% and 88.5%. Detailed information regarding weather can be found in Table 2.2. Considering the importance of the humidity and temperature on perceived comfort [12,13], data of control groups was not combined.

Table 2.2 Weather conditions during the experiment

	Day 1	**Day 2**	**Day 3**
Temperature	17.5	15	17
Humidity	94%	80%	88.5%
Atmosphere pressure	1005 mbar	1010 mbar	998 mbar

Results

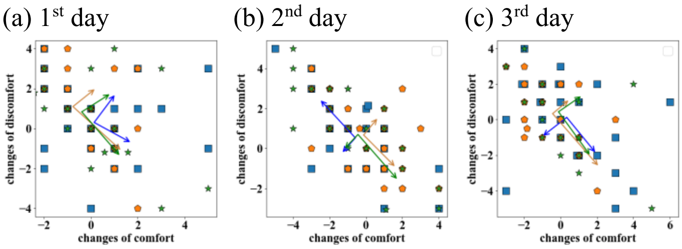
Table 2.3 shows the means and standard deviations of scores of comfort and discomfort in 9 sessions. Two sets of data with statistically significant differences ($p<0.05$) are linked by lines.

Control groups scored quite scattered in the evaluation of comfort at beginning of the three sessions (5.19±1.85, 5.71±1.49, 4.55±1.89). However, when the scents were introduced, the levels of perceived comfort often dropped over time. Compared with the control groups, the smell of mandarin, no matter strong or weak, significantly raised the comfort at the beginning of the experiment ($p<0.05$). For the other 2 scents (lavender and cedar), no significant differences were found when compared with the control groups.

In all sessions, discomfort increased after 60 minutes. Lavender and cedar led to higher discomfort scores compared with the control groups. The intensities regarding lavender and cedar, high intensity led to higher discomfort scores at both the beginning and the end of the experiment. However, the effect of mandarin is different where participants reported lower discomfort scores on high intensity smell.

Table 2.3 Means and standard deviations of scores in 9 sessions (scale 0-10)

	Scents	N	Mean (0min)	SD (0min)	Mean (60min)	SD (60min)
Comfort	**Control 1**	36	5.19	1.85	5.33	1.71
	Weak lavender	30	5.70	1.51	4.93	1.74
	Strong lavender	31	4.97	1.82	4.58	2.14
	Control 2	33	5.71	1.49	5.12	1.52
	Weak cedar	33	5.76	1.62	5.64	1.75
	Strong cedar	33	5.53	1.42	5.09	2.11
	Control 3	29	4.55	1.89	4.89	1.99
	Weak mandarin	24	5.60	1.94	5.17	1.99
	Strong mandarin	18	5.67	1.14	5.56	1.62
Discomfort	**Control 1**	36	3.78	1.64	4.08	2.03
	Weak lavender	30	3.37	1.65	4.47	2.08
	Strong lavender	31	3.97	2.01	4.81	1.94
	Control 2	33	3.62	1.72	4.15	1.97
	Weak cedar	33	3.32	1.55	4.00	1.82
	Strong cedar	33	4.26	1.81	4.94	2.00
	Control 3	29	4.87	1.93	5.00	1.90
	Weak mandarin	24	4.16	2.06	4.50	2.17
	Strong mandarin	18	3.56	1.20	4.00	2.06



(PC1/PC2)	(a) 1st day	(b) 2nd day	(c) 3rd day
Control ■	56.05% / 43.95%	87.55% / 12.45%	69.54% / 30.46%
Light smell ⬟	84.59% / 15.50%	81.36% / 18.64%	91.81% / 8.19%
Strong smell ★	76.91% / 23.09%	90.48% / 9.52%	79.35% / 20.65%

Figure 2.1 The changes of comfort vs the changes of discomfort

For males, significant differences were found between control group 2 (4.60±1.65) and the strong cedar group (4.11±2.52) and between the weak cedar group (4.07±1.94) and the strong cedar group (4.11±2.52) at the end of the experiment regarding discomfort. Differences were also found between control group 3 (4.92±2.06) and the weak mandarin group (5.63±1.67) and control group 3(4.92±2.06) and the strong mandarin group (5.67±1.32) on comfort at the beginning and between control group 3 (4.85±1.91) and the strong mandarin group (3.67±1.58) on discomfort at the beginning. We did not find any significant differences between the female groups although the number of female participants was larger.

Figure 2.1 (a, b and c) present the relations between the changes of comfort and the changes of discomfort over time regarding all three scents, respectively. The PCA showed that for control group 1, the first component (PC1) explains 56.06% of the variation and the second (PC2) explains 43.95%. For the weak lavender group, PC1 explains 84.59% of the variation and the PC2 explains 15.50%. For the strong lavender group, PC1 explains 76.91% while PC2 explains 23.09%. In both scenarios with light and strong smell used, PC1 increases while PC2 decreases, the difference between two components becomes larger. This trend is similar on the second and the third days showing that the scores were more linear in the scenarios with scents, compared to control groups, with the exception of the light smell in day 2. The exact values of different components are shown in Figure 2.1.

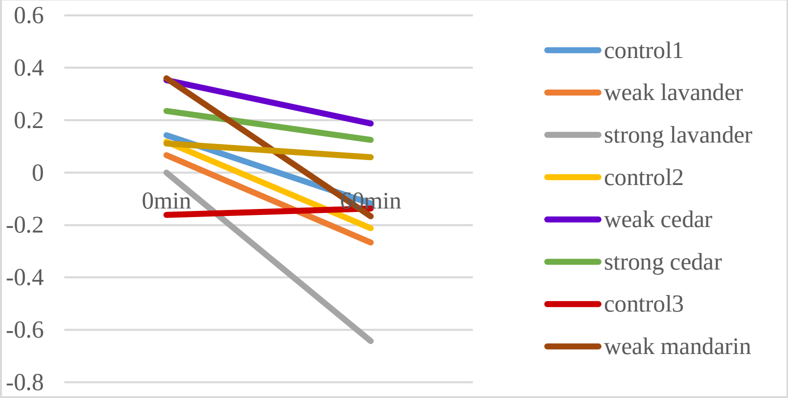


Figure 2.2 Average value change of emotion from beginning to end

Figure 2.2 shows the emotions of nine sessions at the beginning and the end of the experiment. Often, the changes were negative except for control group 3. For weak cedar, strong cedar and strong mandarin, the score decreased less and ended with positive emotion. For participants exposed to lavender, no matter strong or weak, their emotion changed most towards the negative side. No significance was found among scents at the beginning of the experiment. Among all scenarios, a significant change from beginning (0±1.02) to the end (–0.64±0.78) was found for strong lavender only. For different types of scents, significant differences were found between control 1 (–0.09±1.01) and strong lavender (–0.64±0.78) groups, strong lavender (–0.64±0.78) and strong cedar (–0.13±1.01) groups, strong lavender (–0.64±0.78) and strong mandarin (0.06±1.03) groups at the end of the experiment. Compared to the groups using other two scents, the strong lavender group gave the lowest score regarding emotion at the end of the experiment.

Discussion

Effect of scent on comfort/discomfort

Effects of scents on comfort are dependent on the types of scents, the intensity and the gender of participant, and sometimes, no effect could be found. For discomfort the variation was less.

In all circumstances, comfort dropped and discomfort increased after 60 minute exposure to sitting in an aircraft seat which is in accordance with the findings of Vink et al. [77]. Scores on comfort were very dispersed, which could be a result of the variety of personal preference on scents.

Regarding the types of the scents, lavender scored quite negative when calculating the average for discomfort, and also scored negative for emotion. However, it was found that lavender fragrance blend had a significant transient effect of improving mood and increasing a relaxed feeling in an earlier study [78]. The mixture of the context smell in the cabin and the lavender smell might even have caused this effect on the passengers' perception of comfort/discomfort. Slightly better results on both comfort and discomfort were achieved with mandarin. Mandarin could have helped to achieve a better score on comfort since it is linked to food. Positive effects on comfort have been found when food is served in cabin. At the same time, citral in mandarin may help to create a relaxed, pleasant and energetic feeling [79]. Cedar scent in different intensities influenced discomfort differently but there was no difference found between groups with cedar and control groups. The reason could be that the sense and preference are very personal while the smell creates a trend of homogeneity.

Effect of scent on emotion

Changes in emotion for the three control groups were quite different, especially on the 3rd day. The atmosphere pressure on the third day (998mbar) was the lowest in three days (the other two days were 1005mbar & 1010mbar), which may be the reason for the difference. In the study done by Burdack-Freitag et al. [80], it was also observed that odor thresholds of flavorants increase at low pressure conditions. There were few exceptions in the experiment and the odor spectrum of drinks changed differently but it was clear that atmosphere pressure influences the odor thresholds.

In most scenarios, there was no obvious distinction between groups where scents were added and between control groups. This can be a result of the existence of the context smell inside the cabin since the context smell cannot be removed and new scents were mixtures of context smell and added scents. The odor compounds of context smell in cabin still had a major role in the experiments, especially in scenarios with low-intensity scents. Using strong lavender is the only scent which had a significant drop on emotion after the experiment, using weak lavender was significantly better than strong lavender. This suggested that intensity can play an important role on the perception of smell since intensity of a certain smell can strongly influence the feeling of pleasantness [81].

In most circumstances, negative effects were shown both on overall comfort/discomfort and emotion, which shows some correlation between the effects on emotion and comfort as described in previous studies [8,67,82,83].

Gender difference regarding smells

Scent appeared to have influenced males more than females. However, results of previous studies reported that females have more neuronal and non-neuronal cells in their olfactory bulb than males, which might indicate a higher sensitivity to smell [84]. It could be that although females smell these scents, these scents do not influence their comfort or discomfort in an airplane sitting for an hour. However, this should be further researched.

Limitations

The activities for the simulated flight were not exactly the same as in a normal flight. In this experiment the passengers did move in the cabin in order to reduce the impact of physical complaints on overall comfort/discomfort. This (more variation) could have influenced the outcome because this is not often seen in a normal flight situation. Keeping participants seated the entire experiment could be an option in the future to be closer to a real scenario.

To prevent any potential allergy, we informed the participants about the types of essential oils that will be used before the experiment. Outcomes of the experiment might be different if the participants were not informed before.

Design Implications

During data analysis, large variations in outcomes were observed. Although all the participants were in the same environment, the perceived smell differed, which is related to odor receptors due to gene differences [85]. This indicates that forcing passengers to share the same odors in the air might not be a solution to please everyone. The design strategy should not be to “design for average” when utilizing scents in an airplane cabin [86]. This strategy is not typical for scent. The amount of personalized “mass-produced” items is increasing and different brands are seeking opportunities to be more attractive to consumers by offering personalized products as well as services [87]. In the car industry, a gradual change towards accommodating individuality is available [88]. In present day aircrafts, many passengers have the same seat and limited choice of food. In passenger experience research, more differentiation is shown, following the same trend as the car industry. Compared with individual transportation systems, the large diversity in passengers does not make personalization a simple task. However, actions have been already taken, i.e. ordering your food online before a flight. The use of smell in cabin could also be personalized, at least partly personalized. The differences in human olfactory systems between individuals makes personalization in scents more necessary.

Conclusion

Smell influences the perception of comfort and discomfort in an aircraft cabin. The effect of smell differentiates over time and does not only contribute to the first sight comfort/discomfort but also had an impact at the end of the experience in short haul trips. In this experiment the trend of decreasing comfort or increasing discomfort over time did not change by adding scents. In this case, adding scents did make the correlation between change of comfort and change of discomfort more linear. The effects of different scents vary person-to-person and adding more scent to make it stronger was not helpful to achieve better results. Emotion changes were found with different scents and may have resulted in different perceptions of overall comfort/discomfort. It is recommended for future designs regarding diverse individual preferences, to personalize scents or smell in airplane cabins.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Sitting comfort in an aircraft seat with different seat inclination angles

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.

Keywords: aircraft interior, (dis)comfort model, inclination angles, flying experience

Introduction

Passengers’ comfort experience in flights is one of the key elements in selecting airlines [89]. Previous studies have analysed different factors influencing comfort/discomfort, e.g. in-flight service and noise do play a role [90,91]. Among all aspects, seat comfort is one of the most crucial factors influencing comfort experience in the aircraft cabin [5]. Comfort sitting during the cruising stage was studied in the literature for instance regarding the seat pitch [92], seat width [93], sitting duration [77]. 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 [94]. 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° [95].

Many factors might influence comfort of passengers during the climb phase, e.g. getting accustomed to the pressurization [96] and the acceleration [97]. 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 [98]. 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

[99]. Cherng et al. [100] 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 [101]. 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 [26]. 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 [26]. For instance, Yao et al. [102] and Yao et al. [103] 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. [3] used the perceived discomfort questionnaire and Local Postural Discomfort (LPD) questionnaire in studying the effects of active seating on car passengers’ comfort.

Beside subjective feelings, researchers also use different objective measures to evaluate comfort of humans [24]. Among different measurement methods, pressure map has demonstrated its effectiveness in recording the interaction between the human body and the seats (e.g. [42,104–106]). Zemp et al. [107]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 [108]. Akgunduz et al. [109] 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 [110].

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 [111]. Parameters describing HRV 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 (Power density spectrum in the frequency range from 0.04 to 0.15 Hz [112]), HF (Power density spectrum in the frequency range from 0.15 to .40 Hz [112]) and LF/HF (Ratio of LF/HF) were used in previous studies as indicators of different emotions [113,114], and were also applied in comfort studies [26]. For instance, Lorenzino et al. [48] found that acoustic comfort is greatly determined by psychological processes based on the differences between LF, HF and LF/HF regarding these parameters describing HRV. HRV measurement was used in thermal comfort studies as well and it was found that LF/HF varies when the environment temperature changes [115,116].

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?

Methods

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 2.3). 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 [102,117] [118]. 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 2.4). According to Wakefield and Dubuque [95], 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 [119].

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 [120], the wordings in the questionnaires were explained by the researchers prior to the experiment.

Figure 2.3 Participant sitting in the aircraft seat in a Boeing 737 aircraft cabin.

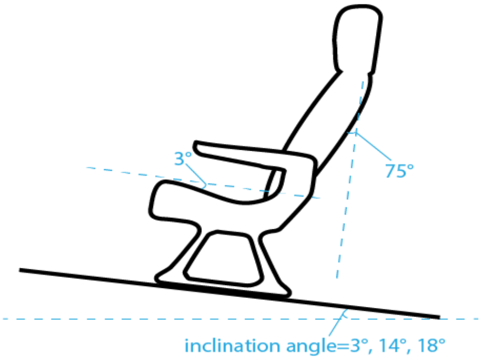


Figure 2.4 Schematic diagram of the aircraft seat in the experiment and the settings with three different inclination angles.

Protocol

The procedure of the experiment can be found in Fig 2.5. As the duration of the climbing phase is about 20–30 min [121], participants experienced each set up, i.e. setting 1, 2, and 3, for about 20 min in three sessions. In each session, a participant was asked to complete the comfort/discomfort questionnaire right after sitting down. Then he/she completed the same questionnaire again after 10 min. At 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. Due to individual preferences and habits, the head is not always in contact with the seat, so the pressure on the headrest was not recorded.

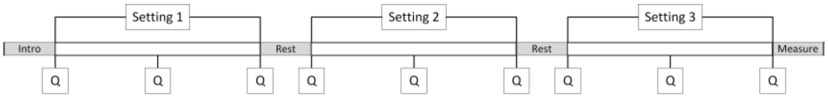


Figure 2.5 Procedure of the experiment (Q: participants filling in the questionnaire).

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.

Figure 2.6 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. [122], 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 $\overrightarrow{LC} = \frac{\sum_{i=1}^{n} P_i * \overrightarrow{L_i}}{\sum_{i=1}^{n} P_i}$, where P_i is the recorded pressure value in a cell, $\overrightarrow{L_i}$ 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 $V_C = \frac{\sum_{j=1}^{m-1} |\overrightarrow{LC_{j+1}} - \overrightarrow{LC_j}|}{(m-1)*t}$, where $\overrightarrow{LC_j}$ 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.

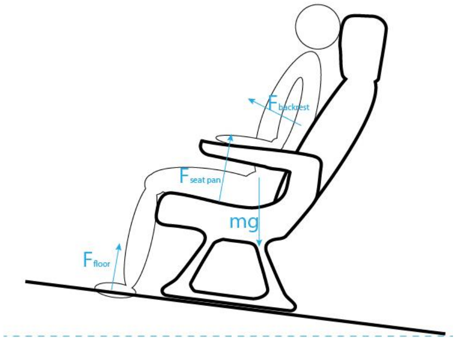


Figure 2.6 Approximate free body diagram of passengers sitting in the aircraft seat with an inclination angle.

Parameters describing HRV 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 parameters describing HRV and (dis)comfort were reported as well.

Results

Comfort

Comfort and discomfort scores are shown in Figure 2.7. 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 discomfortable 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.

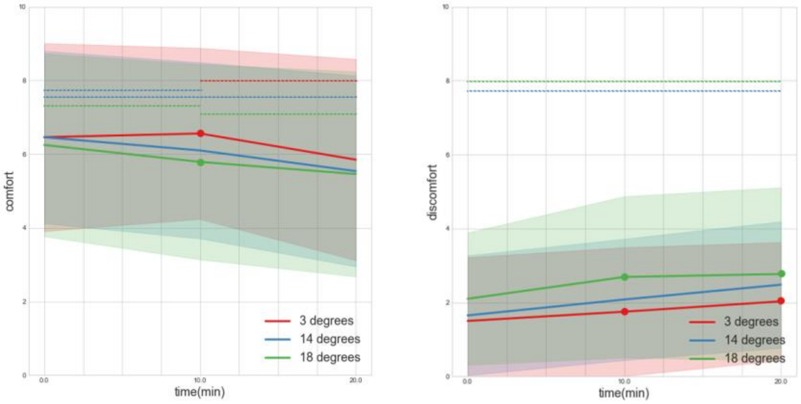


Figure 2.7 Absolute scores of perceived comfort and discomfort in 20 minutes with the standard deviation in a lighter color (0=no (dis)comfort at all, 10=extreme (dis)comfort). Significant differences ($p<0.05$) between settings at the same points are marked with dots. Significant differences ($p<0.05$) between time points in the same settings are connected with top horizontal dash lines.

Pressure

The values of the mean pressure, peak pressure and contact areas on the backrest are shown in Table 2.4. 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 2.5 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 2.4 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 2.5 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/cm^2)	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/cm^2)	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(cm^2)	1077.27±169.19	1116.13±151.10	1136.97±135.36	3-18,p=0.024

Table 2.6 shows the force on the backrest and the seat pan in three different settings. Table 2.7 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 2.8 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.

Table 2.6 Total forces given by the backrest and the seat pan in three settings (unit=N).

	3 degrees	14 degrees	18 degrees
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

Table 2.7 The contribution of forces given by the backrest, the seat pan and the floor to hold the subject on vertical direction.

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

Table 2.8 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

HRV

Table 2.9 Parameters describing HRV 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

Parameters describing HRV 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 2.9. Compared with the 3-degree setting, the LF is significantly lower when participants are sitting with an inclination angle of 18 degrees. The LF/HF of participants in both 14-degree and 18-degree settings are lower than in the 3-degree setting. The correlations of these features to comfort and discomfort are shown in Table 2.10. Correlations with p values under 0.05 are considered significant. Significant correlations were 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 parameters describing HRV.

Table 2.10 Correlations between parameters describing HRV 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

Discussion

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. [123] 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 [121], most complaints 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. [124] indicated that 119° between upper leg and back is preferred by passengers sitting in car seat. Smulders et al. [125] concluded that 121° is the preferred angle for passive relaxing sitting with the seat pan slightly reclines. Groenesteijn [126] 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 [40,127]. The values of comfort after 20 min are rather low compared with the literature. For instance, Anjani et al. showed that these values lower than 6 are comparable with seats smaller than 17 inch wide and a pitch lower than 30 inch [93]. At the 18-degree setting the values were already lower than 6 after 10 min.

Pressure

Compared with the 14-degree setting, significantly less mean pressure and peak pressure on the seat pan were shown in the 18-degree setting. Previous studies indicated that mean pressure and peak pressures are negatively correlated to perceived comfort [108] [128]. 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 [129]. 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 [130]. 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 [131]. 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 [40].

Compensatory movements

Table 2.7 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 2.8). 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 [41], 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 [92]. 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.

HRV

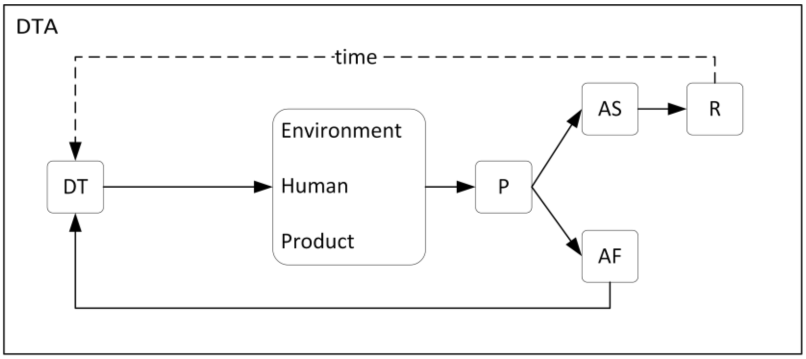
In this study, some parameters describing HRV were correlated to comfort. As '*comfort is seen as a pleasant state or relaxed feeling of a human being in reaction to its environment'* [10], the correlation can be clarified. The mental status and the psychological stress can influence comfort directly. In previous studies, SDSD was reported to be sufficient in showing the difference in the Trier Social Stress Test (TSST) measured by the mood questionnaire (MDBF) and progressive muscle relaxation (PMR) [132,133]. Trends in RMSSD can show significant differences in different stress levels [134]. Significant changes of HF was also found regarding stress levels [134]. However, no correlation between parameters describing HRV and discomfort was found in this study. In the study requiring 2-h sitting period, correlations were found between discomfort and multiple parameters describing HRV including SDNN, LF, HF and non-linear parameters [26]. Since HRV is a sensitive indicator reflecting central–peripheral neural feedback and CNS (central nervous system)–ANS (autonomic nervous system) integration [135], 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 [67] and less to emotions and therefore less to parameters describing HRV. Comfort might be more related to emotions and thereby to parameters describing HRV.

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 Figure 2.8) as a supplement to the comfort model proposed by Vink and Hallbeck [10] and later further detailed by [136].

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 subject fails to make the adjustment and the discomfort remains.

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 degrees, subjects could easily have the discomfort reduced through movements. In the setting with the inclination angle of 18 degrees, subjects kept moving, but were restricted during moving by safety belts and the changed gravitational force direction. [131] reported an increase in COP movements over time, which is probably more difficult in the reclined condition with the result of an increase in discomfort. This loop is assumed to happen less in the setting with the inclination angle of 14 degrees since the movement was the slowest.



DT=discomfort trigger, P= perceived effects, AS= adjustment successful, AF= adjustment failed, R= discomfort reduced

Figure 2.8 DTA process in explaining the relation between discomfort, movement and the environment.

The DTA process has links to the Fogg Behavior Model [137]. 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.

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 [138]. 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.

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-degree and the 18-degree settings, the perceived comfort and discomfort in the 14-degree setting were closer to the cruising angle setting (3°). The discomfort of 18-degree setting is significantly higher compared with the 3-degree setting, 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 setting 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.

Acknowledgement

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3. Comfort measurements

This chapter is based on following papers:

1. Yao X, He Y, Udomboonyanupap S, Hessenberger N, Song Y, Vink P. Measuring pressure distribution under the seat cushion and dividing the pressure map in six regions might be beneficial for comfort studies of aircraft seats. Ergonomics. 2022. doi:10.1080/00140139.2022.2157495
2. Yao X, Yang Y, Vledder G, Xu J, Song Y & Vink P. Comfort wearables for in-flight sitting posture recognition. Accepted by IEEE Access .

Measuring pressure distribution under the seat cushion and dividing the pressure map in six regions might be beneficial for comfort studies of aircraft seats

Abstract

Seat pressure maps are often used to evaluate comfort of the users. In this study, we explored the relationships between pressure maps and comfort/discomfort of users in aircraft seats with a focus on a new 6-division method on the pressure maps collected at the bottom of the cushions. An experiment was designed where three cushions with identical shapes but different stiffnesses were prepared. 33 subjects joined the experiment and after sitting on each cushion in 4 postures, they completed comfort questionnaires. Pressure maps on the top as well as the bottom of cushions were collected and analysed. Results indicated that measures on the proposed 6 divisions, especially on the distal posterior thigh regions and regions close to ischial tuberosity of the bottom pressure maps, had larger correlation values to comfort scores compared to other division methods.

Keywords: pressure maps, measures, division, aircraft seat

Practitioner Summary

The relations between comfort/discomfort and seat pressure maps collected from the top/bottom of three cushions were studied with 33 subjects in four postures. The distal posterior thigh and ischial tuberosity regions in the proposed 6-division of the bottom pressure maps had larger correlation values to comfort/discomfort compared to other methods.

Introduction

During a flight, train ride or bus ride passengers spend most of their time sitting. Previous research indicated that the perceived sitting comfort and discomfort are of significant importance for passengers when choosing an airline [139], and a well-designed seat plays a vital role in enhancing comfort experience of passengers [140].

While sitting, the human body is in direct contact with the seat (cushion) and the interface pressure profile between the body and the seat (cushion), which can be captured by a pressure sensing mat as a pressure map [24,141], has relations with the perceived discomfort [67]. As the hip joints are often fixed during sitting and the weight is mainly sustained by the bony structure [142], distribution of pressure values or pressure distribution in the pressure map is not uniform and a large pressure concentrated area can always be found in the region around the ischial tuberosity [143], followed by the proximal posterior thigh.

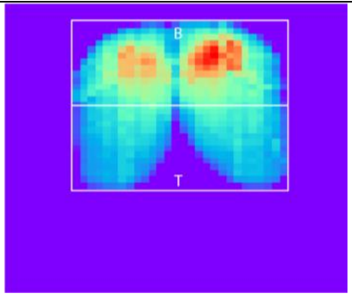
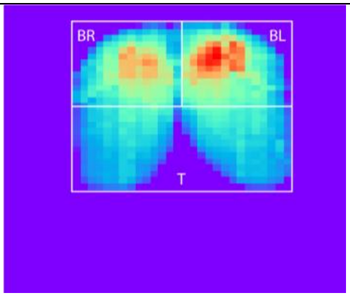
Pressure distributions of people sitting in car seats were studied often to improve comfort of drivers/passengers and reduce potential health risks [43,52,106]. Though the backrest recline angle, the posture, and the armrest might influence the supporting forces of a person regarding different seat components while sitting, the seat cushion usually takes 55–95% of the weight [144]. In the study of Ebe and Griffin [145], it was found that the ‘bottoming feeling’ and the ‘foam hardness feeling' were two main factors influencing comfort of a seat, which were affirmed by other studies [146,147]. Zemp et al. [107] showed that less discomfort and higher comfort are related to a lower mean pressure, a lower peak pressure, and a larger contact area(s) of the pressure map. Akgunduz et al. [109] also found correlations between perceived comfort and the peak and mean pressures on the seat pan.

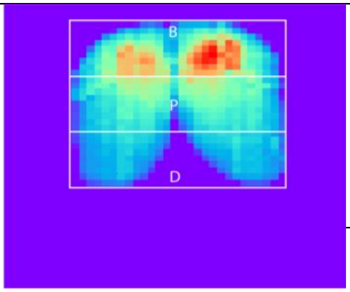
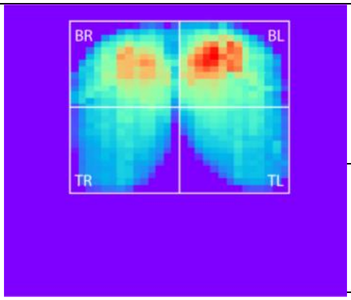
To highlight the importance of different regions of the seat cushion regarding comfort/discomfort for possible improvements, researchers tried to divide the pressure map into different regions following different criteria. For instance, Kilincsoy [43] uniformly divided the bounding box of the contact area by a 3 × 2 grid following the fore-aft and lateral directions, respectively. He found that in the back seat of an SUV, the ideal pressure distribution for comfort can be <55.8%, <20.0%, <9% regarding the buttock, the proximal posterior thigh and the distal posterior thigh, respectively. Lantoine et al. [42] introduced the crotch point as a landmark to divide the bounding box into four regions and they found that the values of contact pressure in the left buttock region were significantly higher than other areas. Table 3.1 listed the divisions that proposed in previous studies, their application contexts, and the main findings.

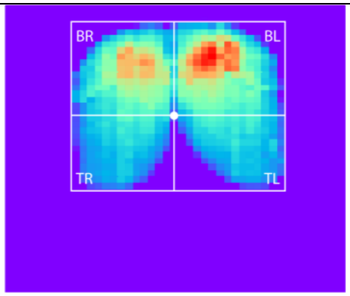
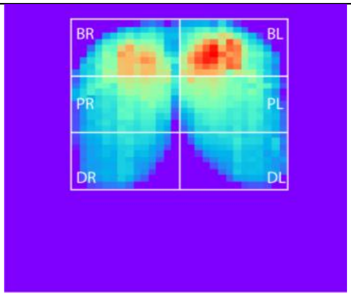
Researchers paid extensive effort in using the pressure map measures to explain the perceived comfort/discomfort of users. However, many division methods are subjected to the shape of contact areas regarding different seats, e.g. only a few studies investigated the pressure distribution of aircraft seat regarding comfort [118]; there is no consensus on the use of pressure map measures regarding the perceived comfort/discomfort; and the pressure mat, which uses different materials compared to the upholstery of the seat, is often positioned on the top of the cushion [148,149]. This limits the comparison of different comfort and discomfort evaluations and it is the question which is most valuable, especially for long-term evaluation.

In this study, we tried to explore the relationships between comfort/discomfort and measures in different regions of pressure maps captured on the top as well as the bottom of the cushion in the context of aircraft seats. The research questions were set as (1) Which division methods and pressure map measures are more suitable for evaluating comfort/discomfort experience of passengers and (2) Can the relationships between comfort/discomfort and the pressure map captured from the bottom of the cushion be established?

Table 3.1 Different divisions of the pressure distribution used in past studies

No. Regions (Name of the method)	Division methods	Application context	Information of participants	Main outcomes	Literature
2 (2A)	 The pressure map is divided into two equal parts: buttock area and thigh area.	Driver seat	16 healthy males Age 25.5±2.6 years Height 172.8±5.4 cm Weight 72.3±9.8 kg Driving experience 2.38±2.4 years	It is possible to use the dynamic pressure data as a tool for the assessment of driver discomfort. The pressure measures in different regions change in different driving period.	[104]
3 (3A)	 The pressure map is divided equally into buttock area and thigh area. The buttock area is divided equally into right and left.	Office chair	18 participants (9males, 9 females) Mean age 22.4 (males),23.8 (females) Height 159-183cm(males),158-173cm(females) Weight 45-82kg(males), 41-104kg(females)	The type of sitting posture has significant influence on the pressure distributions in different regions, thus postures in seat can be detected.	[105]

3 (3B)	 The pressure map is equally divided into three parts with two horizontal lines.	Car seat	48 participants (24males,24 females) Age 18-29 years Male height 178-182cm, weight 72-76kg Female height 165-169cm, weight 58-62kg	Ideal pressure distribution should have 56±7% load at buttock, 30±3.5 at upper thigh,8±4.4% at lower thigh.	[106]
		School chair	27 participants (15males,12females) Age 24.37±2.35years Height 170.19±8.68cm Weight 69.56±13.9kg BMI 23.77±2.95	The study investigated the relationships between comfort, human body postures, pressure at interface, and load distribution on the contact area. Measures with the largest correlation is in region D.	[150]
		Aircraft seat	22 participants (13 males, 9 females) Age 19-29 years BMI P4-P78	The study recorded the pressure map with different cushions and compared the load in each regions. Significant differences were found between pressure measures within the same regions of different cushions.	[118]
4 (4A)	 The pressure map is divided into 2 x 2 regions equally.	Driver seat	27 participants (12 males,15 females) Age 20-35 years Weight 69.1±13.1kg Height 170.7±11.7cm	The largest correlation between pressure map measures and overall rating was found in region BL.	[151]
		Office chair	27 participants(15males and 12 females) Age 24.37±2.35 years BMI 23.77±2.95	Contributions of different regions are not clear but the study confirmed that the pressure measures are different with different sit pitches.	[152]
		Aircraft seat	12 participants (7 males, 5 females) Height 176.2±7.34cm(males), 163.8±4.9cm(females)	Seat pitch can significantly influence the contact area of BR region while seat conditions can change the peak pressure in BL,TL and TR regions.	[153]

			Weight 77.5±13.1kg(males), 55±5.9kg(females) BMI 24.8±2.9(males), 21±2.1(females)		
4 (4B)	 The pressure map is divided into four parts by a vertical and a horizontal line through the crotch point.	Driver seat	20 participants (10 males, 10 females) Age 27.8 ± 5.6 years Height 1.73 ± 0.1 m Weight 69.9 ± 14.4 kg	The study proposed a division based on the location of crotch. The highest pressure shown in BL region and the largest contact area shown in TR region.	[42]
6 (6A)	 The pressure map is divided into six parts equally with two horizontal lines and a vertical line.	Car seat	50 participants (30 males, 20 females) Age 21-53 years Height percentiles 0.1-99.5	Ideally, the load on each region should be 29.5% at buttock, 9.7% at upper thigh and 3.1% at lower thigh on each side of the body.	[43]

***B/T: buttock/thigh region; D/P: distal/proximal posterior thigh region; BL/BR: buttock left/right region; TL/TR: thigh left/right region; DL/DR/PL/RL: distal/proximal posterior thigh left/right**

Methods

Postures

Passengers experience differs in comfort and discomfort in different postures in an aircraft seat. In the study conducted by Liu et al. [28], the different postures and the frequency of occurrences in aircraft cabins were summarized. Four postures were selected for this study (Figure 3.1): (1) sit with two feet on the ground, hands on lap, both head and back against the backrest; (2) sit with two feet on the ground, back against the backrest, head down to look at the phones/books in hands on lap; (3) sit straight with feet on ground and hands on lap; and (4) sit with feet on the ground, back against the backrest, holding phones in front of the chest and look into the phones. These four postures account for 29.7%, 12.9%, 4.2% and 3.2% of the occurrences, respectively [28] .

(1) (2) (3) (4)

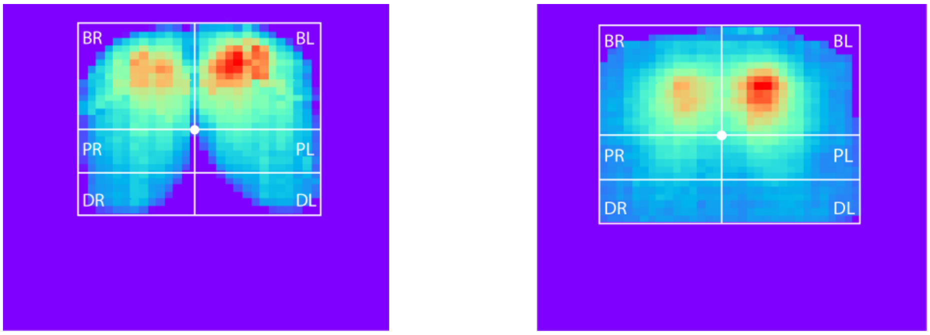
Figure 3.1 Four postures selected in this study

Figure 3.2 Three cushions with different stiffnesses used in this study (A,B,C from left to right)

Participants and Protocols

To collect the pressure maps on the top as well as at the bottom of the cushions with these 4 postures, 33 subjects, 18 males and 15 females ageing from 23 to 37 (BMI between 17.6 and 41.3), were invited to a within-subject experiment. Two rows of aircraft seats were used in this experiment to simulate the flying environment. In the 2nd row three self-designed NEVEON® cushions with the same shape but different stiffnesses were evaluated on an economy class seat frame (see Figure 3.1). The cushions were designed with a depth of 50 cm and a width of 44 cm (17.3 inch). The thicknesses of all cushions were 6 cm. To ensure the fit of the cushions and the frame of a 17-inch-wide seat, two triangular parts (8 and 10 cm for two sides adjacent to the right angle of the orthogonal triangle) were cut off from the upper edges (see Figure 3.2). All cushions are being used in aircraft seats and cushion A is the softest while cushion C is the hardest. Compression tests were done with Zwick Z010 on three points of each cushion and five times each point. The average displacements under 125 N on the compression plate (Φ 30 mm) are 48.6 mm, 38.1 mm and 31.6 mm. Subjects sat on each cushion for about 12 min. The pressure map of each posture was recorded on the top and at the bottom of the seat cushion using two XSensor LX210:48.48.02 pressure sensing mats (resolution: 48 × 48 cells, each 1.27 cm × 1.27 cm). The sequence of the cushions for each participant was altered using the Latin Square method. After experiencing a cushion, participants were asked to complete an overall comfort and discomfort questionnaire [154].

Data analysis methods



(a) Top (b) Bottom

Figure 3.3 Proposed division (Method 6B) on the top as well as the bottom pressure map

The comfort/discomfort scores of the questionnaires were normalised using the min-max scaling [155]. To divide the pressure map to different regions, besides the six division methods (2A, 3A, 3B, 4A, 4B, 6A) summarised in Table 3.1, we proposed a new division (6B, as Figure 3) by combining the six-region division used by Kilincsoy [43] and the four-region division used by Lantoine et al. [42]. Similar to the work of Lantoine et al. [42], the highest point on the edge of buttock between two thighs on the pressure map was used as the approximation of the crotch on the upper layer (round dots in Figure 3.3). The location of crotch on the lower pressure map was defined as the projection of the crotch point on the upper layer. In the bounding box of the contact area, we divided the pressure map to 4 regions using the crotch point. The two posterior thigh regions were further divided by a line in the middle to roughly outline the distal and proximal posterior thigh regions, as Kilincsoy [43] concluded that the distal posterior thigh might be more sensitive to the proximal side regarding the same pressure.In Table 3.2, literature regarding pressure map measures and perceived sitting comfort/discomfort in different contexts is listed. Based on these studies, eight measures were selected for this study: mean pressure, peak pressure, contact area (CA), variance (VA), coefficient of variation (CV), force, load and seat pressure distribution percentage (SPD%). The mean pressure was the mean of all pressure values in the contact area, the peak pressure was calculated as the mean of the five largest pressure values in the contact area. Variance was calculated as the square of standard deviation of pressure values of the valid cells. Coefficient of Variation (CV) was the square root of the variance, i.e. the standard deviation, divided by the mean pressure. The total force applied on the pressure mat can be calculated as the sum of forces applied on all cells (pressure × area). Load is the ratio between force in each region and the total force. SPD% $= \sum_1^n (p - \bar{p})^2 / 4n\bar{p}^2 \times 100\%$ [156], where $\bar{p}$ stands for the mean pressure, p stands for the pressure in each valid cell and n is the number of cells in the contact area.

For each subject regarding each cushion, eight pressure recordings (four postures × the upper and lower) were collected. Using the seven division methods (six in Table 3.1 and the proposed new method in Figure 3.3), we computed eight measures of each region of the pressure map. According to Liu et al. [28], the occurrence of the four postures in a 2h flight journey account for 29.7%, 12.9%, 4.2% and 3.2% of the total. These percentages were used as weights for the calculation. For each cell in the pressure map regarding 4 postures, the weighted average pressure value fv was computed as fv $= \sum_{i=1}^{4} w_i \mathrm{fv}_i \,/ \sum_{i=1}^{4} w_i$. Here $w = [29.7\%, 12.6\%, 4.2\%, 3.2\%]$ and fv_i stands for the pressure values of each posture. For the scores of comfort discomfort questionnaires, Min–Max normalisation [155] has been processed with subjective data to show the changes in comfort and discomfort, as compared to use the absolute scores of subjective ratings on comfort/discomfort, using the relative changes of the comfort/discomfort might be less influenced by the background the expectations of subjects [24]. Pearson correlation coefficients between measured values in different regions and normalised comfort/discomfort scores were calculated regarding all subjects and 3 cushions. Measures with the largest three correlations were highlighted regarding this region.

Table 3.2 Pressure measures regarding sitting comfort

context	Pressure measures	Subjective measures	Number of participants	Main outcomes	literature
Wheelchair	Contact area Mean pressure Peak pressure Peak pressure index Dispersion index	Self-designed questionnaire with questions covering comfort, adaptability and thermal sensation.	22	No clear recommendations regarding measures were given but these measures were used as indicators for evaluating seat cushions and satisfaction.	[157]
Office chair	Mean pressure Peak pressure Contact area Max pressure gradient	Seat cushion comfort ratings regarding support of the cushion and skin pressure.	16	**Mean pressure** and **peak pressure** are significantly correlated to perceived comfort.	[128]
School chair	Peak pressure Mean pressure Contact area Load	Local Postural Discomfort in buttock and thigh areas.	27	A positive correlation between perceived discomfort and **contact area** was found.	[150]
Aircraft seat	SPD%	NA	-	**SPD%** was used as a parameter to indicate	[156]

				sitting comfort and guide seat design.	
Driver seat	Contact force Contact force ratio Peak pressure Mean pressure Contact area	Local Postural Discomfort, stiffness rating and wrapping rating.	8	A strong correlation was found between comfort and **peak pressure** as well as **mean pressure.**	[109]
Surgery seat	Mean pressure Peak pressure Median pressure Standard error Mode Standard deviation variance Contact area	Comfort, Local Postural Discomfort and preference of conditions.	11	Comfort is related to **low peak pressure** and high **contact areas** of the seat pan.	[108]
Driver seat	Contact area Contact area ratio Mean pressure Peak pressure Contact pressure ratio	Overall rating, overall comfort, overall discomfort, body region comfort and Local Postural Discomfort.	27	**Contact area** and **contact pressure ratio** could be used for evaluating sitting comfort/discomfort.	[151]

Results

In Table 3.3, the mean pressure and its standard deviation (SD) of each posture regarding each cushion are listed. In general, the mean pressure and its SD on the top layer were both larger than that of the bottom layer, whereas for the softest cushion (A), both were the smallest. With the hardest cushion (C), the largest mean pressure was observed both on the top and the bottom pressure maps.

Table 3.4 to Table 3.10 present measures with the 3 highest correlations to comfort/discomfort for each division method. The absolute values of correlations (AVC) under 0.1 are not included in these tables. The AVC $\geqslant$ 0.3 measures are highlighted. Table 3.4 shows that more AVCs $\geqslant$ 0.3 were found in the thigh region than the buttock region using method 2A. Compared to discomfort, more AVCs between comfort and pressure parameters are over 0.3. Twelve AVCs are highlighted in Table 3.5 (method 3A), where the pressure map was divided into right buttock region, left buttock region and thigh region. The highest correlation is 0.447, which was found in the left buttock region. More AVCs $\geqslant$ 0.3 were found between pressure and comfort both on upper layer and lower layer with division Method 3B (Table 3.6). For using method 4A (Table 3.7), results in the buttock regions are similar to that of using the division method 3A (Table 3.5). The division of the thigh regions suggested that the pressure measures of right thigh might be more correlated to comfort. Results of using the other 2 by 2 division method (4B) are shown in Table 3.8, in which the division is based on the crotch point. Compared to the uniform division methods, e.g. method 4A in Table 3.7, more correlations with AVC ⩾ 0.3 were found. Both the buttock region and the thigh region on the right side show better performance than those of the left. The results of dividing the pressure map into 6 regions equally are shown in Table 3.9. Most of correlations over 0.3 are in the buttock regions and distal posterior thigh regions. Only 3 out of 22 of them are in proximal posterior thigh regions. The results of proposed 6-division method (Method 6B) are shown in Table 3.10. The correlations between pressure measures and (dis)comfort in buttock regions are the same with the results of division method 4B (Table 3.8). Compared to method 6A (Table 3.9), more correlations over 0.3 were found in proximal posterior thigh regions, mostly on the right side. In total, 24 correlations were highlighted with the proposed method. Among the 7 division methods, method 6B (Figure 3.3), had the most measures that had AVCs ⩾ 0.3, which were mostly centred on the bottom layer. The individual measure with highest correlations to (dis)comfort in different regions of cushions with varying siffnesses are not consistent. The absolute values of the highest correlations also do not always exceed 0.3.

Table 3.3 Mean pressure of each posture for each cushion at the top and the bottom (unit: N/cm^2)

	Cushion A top	Cushion A bottom	Cushion B top	Cushion B bottom	Cushion C top	Cushion C bottom
Posture1	0.59±0.08	0.45±0.04	0.65±0.11	0.56±0.05	0.69±0.12	0.57±0.06
Posture2	0.56±0.06	0.42±0.02	0.60±0.09	0.52±0.04	0.63±0.08	0.52±0.04
Posture3	0.55±0.06	0.41±0.02	0.61±0.10	0.52±0.04	0.64±0.09	0.53±0.04
Posture4	0.55±0.06	0.41±0.02	0.60±0.10	0.52±0.04	0.64±0.08	0.52±0.04

Table 3.4 Highest correlations(5 AVCs≥0.3) in buttock and thigh regions (Method 2A) on different layers of three cushions (CA: contact area, VA: variance, CV: coefficient of variation, SPD%: seat pressure distribution percentage)

Buttock region (B)	Upper layer comfort	A: CA B: CA C: CV	0.208 0.164 0.204
	Upper layer discomfort	A: CV B: CA C: CA	0.219 -0.164 -0.264
	Lower layer comfort	A: CA B: Force C: -	0.345 0.197 -
	Lower layer discomfort	A: Load B: CA C: CA	0.163 -0.22 -0.253
Thigh region (T)	Upper layer comfort	A: CA B: CA C: CA	0.363 0.193 0.191
	Upper layer discomfort	A: CA B: VA C: SPD%	-0.154 0.335 0.267
	Lower layer comfort	A: Force B: CA C: Peak	0.34 0.318 0.104
	Lower layer discomfort	A: Force B: Load C: CA	-0.185 0.17 -0.195

Table 3.5 Highest correlations (12 AVCs≥0.3) in buttock right, buttock left and thigh regions(Method 3A) on different layers of three cushions (CA: contact area, VA: variance, CV: coefficient of variation, SPD%: seat pressure distribution percentage)

Buttock right region(BR)			Buttock left region(BL)		
Upper layer comfort	A: Load B: Load C: CV	-0.441 -0.243 0.19	Upper layer comfort	A: Force B: Force C: Load	0.285 0.447 -0.227
Upper layer discomfort	A: Load B: CA C: CA	0.351 -0.212 -0.289	Upper layer discomfort	A: CV B: Force C: CA	0.234 -0.342 -0.229
Lower layer comfort	A: Mean B: CA C: -	0.254 0.204 -	Lower layer comfort	A: CA B: Force C: -	0.431 0.295 -
Lower layer discomfort	A: CA B: CA C: Mean	-0.112 -0.319 0.345	Lower layer discomfort	A: Force B: CV C: CA	-0.122 -0.399 -0.218
Thigh region(T)					
Upper layer comfort	A: CA B: CA C: CA	0.363 0.193 0.191			
Upper layer discomfort	A: CA B: VA C: SPD%	-0.154 0.335 0.267			
Lower layer comfort	A: Force B: CA C: Peak	0.34 0.318 0.104			
Lower layer discomfort	A: Force B: Load C: CA	-0.185 0.17 -0.195			

Table 3.6 Highest correlations (9 AVCs≥0.3) in buttock, proximal posterior thigh and distal posterior regions (Method 3B) on different layers of three cushions (CA: contact area, VA: variance, CV: coefficient of variation, SPD%: seat pressure distribution percentage)

Buttock region(B)	Upper layer comfort	A: Load	-0.305
		B: CA	0.162
		C: CV	0.272
	Upper layer discomfort	A: CA	-0.242
		B: CA	-0.148
		C: CA	-0.273
	Lower layer comfort	A: CA	0.425
		B: Load	-0.178
		C: Load	-0.122
	Lower layer discomfort	A: CA	-0.244
		B: CA	-0.223
		C: CA	-0.306
Proximal posterior thigh(P)	Upper layer comfort	A: CA	0.351
		B: CA	0.205
		C: Peak	0.213
	Upper layer discomfort	A: CV	0.296
		B: Mean	0.136
		C: CA	-0.203
	Lower layer comfort	A: Mean	0.305
		B: CA	0.246
		C: Force	0.134
	Lower layer discomfort	A: SPD%	0.199
		B: CA	-0.155
		C: CA	-0.142
Distal posterior thigh(D)	Upper layer comfort	A: CA	0.347
		B: CA	0.168
		C: CA	0.209
	Upper layer discomfort	A: CA	-0.138
		B: VA	0.375
		C: CA	-0.234
	Lower layer comfort	A: VA	0.312
		B: CA	0.327
		C: Peak	0.11
	Lower layer discomfort	A: VA	-0.213
		B: Mean	0.156
		C: CA	-0.206

Table 3.7 Highest correlations (17 AVCs≥0.3) in buttock right, buttock left, thigh right and thigh left regions (Method 4A) on different layers of three cushions (CA: contact area, VA: variance, CV: coefficient of variation, SPD%: seat pressure distribution percentage)

Buttock right region(BR)	Upper layer comfort	A: Load B: Load C: CV	-0.441 -0.243 0.19	Upper layer comfort	A: Force B: Force C: Load	0.285 0.447 -0.227	Buttock left region(BL)
	Upper layer discomfort	A: Load B: CA C: CA	0.351 -0.212 -0.251	Upper layer discomfort	A: CV B: Force C: CA	0.234 -0.342 -0.123	
	Lower layer comfort	A: Mean B: CA C: -	0.254 0.204 -	Lower layer comfort	A: CA B: Force C: -	0.431 0.295 -	
	Lower layer discomfort	A: CA B: CA C: Mean	-0.118 -0.319 0.345	Lower layer discomfort	A: Force B: CV C: CA	-0.122 -0.399 -0.218	
Thigh right region(TR)	Upper layer comfort	A: CA B: SPD% C: SPD%	0.352 0.318 0.33	Upper layer comfort	A: CA B: CA C: CA	0.364 0.194 0.147	Thigh left region(TL)
	Upper layer discomfort	A: CA B: VA C: SPD%	-0.169 0.302 0.29	Upper layer discomfort	A: CA B: VA C: CA	-0.136 0.318 -0.129	
	Lower layer comfort	A: VA B: CA C: Load	0.308 0.354 0.158	Lower layer comfort	A: Force B: CA C: Force	0.384 0.267 0.121	
	Lower layer discomfort	A: Mean B: CA C: CA	-0.185 -0.219 -0.231	Lower layer discomfort	A: Force B: Load C: SPD%	-0.194 0.26 -0.239	

Table 3.8 Highest correlations (21 AVCs≥0.3) in buttock right, buttock left, thigh right and thigh left regions(Method 4B) divided based on crotch location on different layers of three cushions (CA: contact area, VA: variance, CV: coefficient of variation, SPD%: seat pressure distribution percentage)

Buttock right region(BR)	Upper layer comfort	A: Mean B: Mean C: CV	0.376 -0.229 0.251	Upper layer comfort	A: SPD% B: Force C: Peak	0.264 0.453 0.13	Buttock left region(BL)
	Upper layer discomfort	A: Load B: Mean C: Load	0.234 0.161 0.278	Upper layer discomfort	A: Load B: Force C: Mean	0.471 -0.144 -0.138	
	Lower layer comfort	A: Force B: CA C: Force	0.403 0.328 0.422	Lower layer comfort	A: Peak B: CA C: CA	0.181 0.398 0.31	
	Lower layer discomfort	A: Force B: CV C: Mean	-0.102 0.357 0.313	Lower layer discomfort	A: CV B: CA C: Force	0.274 -0.135 -0.127	
Thigh right region(TR)	Upper layer comfort	A: Force B: Load C: SPD%	0.166 -0.174 0.373	Upper layer comfort	A: VA B: Load C: -	0.176 -0.174 -	Thigh left region(TL)
	Upper layer discomfort	A: Force B: VA C: VA	-0.3 0.388 0.236	Upper layer discomfort	A: CV B: Mean C: CV	0.12 0.359 0.323	
	Lower layer comfort	A: Mean B: Load C: VA	0.254 -0.345 0.322	Lower layer comfort	A: Mean B: Mean C: Mean	0.301 0.431 0.367	
	Lower layer discomfort	A: Force B: SPD% C: Peak	-0.353 0.123 -0.154	Lower layer discomfort	A: Mean B: Peak C: Mean	-0.187 -0.194 -0.292	

Table 3.9 Highest correlations (21 AVCs≥0.3) in buttock right, buttock left, proximal posterior thigh right, proximal posterior thigh left, distal posterior thigh right and distal posterior thigh left regions (Method 6A) on different layers of three cushions(CA: contact area, VA: variance, CV: coefficient of variation, SPD%: seat pressure distribution percentage)

Buttock right region(BR)	Upper layer comfort	A: Load B: Load C: CV	-0.441 -0.243 0.189	Upper layer comfort	A: Force B: Force C: Load	0.285 0.447 -0.214	Buttock left region(BL)
	Upper layer discomfort	A: Load B: CA C: Mean	0.351 -0.212 0.271	Upper layer discomfort	A: CV B: Force C: CA	0.234 -0.342 -0.17	
	Lower layer comfort	A: Mean B: CA C: -	0.254 0.204 -	Lower layer comfort	A: CA B: Force C: -	0.431 0.295 -	
	Lower layer discomfort	A: CA B: CA C: Mean	-0.118 -0.319 0.345	Lower layer discomfort	A: Force B: CV C: CA	-0.122 -0.399 -0.218	
Proximal posterior thigh right region(PR)	Upper layer comfort	A: CA B: CA C: VA	0.325 0.202 0.24	Upper layer comfort	A: CA B: Peak C: CV	0.365 0.212 0.154	Proximal posterior thigh left region(PL)
	Upper layer discomfort	A: CV B: Mean C: CA	0.268 0.173 -0.2	Upper layer discomfort	A: CV B: - C: Load	0.299 - 0.193	
	Lower layer comfort	A: Mean B: CA C: Mean	0.264 0.273 0.174	Lower layer comfort	A: Force B: Peak C: Force	0.334 0.275 0.12	
	Lower layer discomfort	A: SPD% B: CA C: SPD%	0.148 -0.253 0.222	Lower layer discomfort	A: CV B: CV C: Load	0.192 -0.265 0.116	
Distal posterior thigh right region(DR)	Upper layer comfort	A: CA B: SPD% C: SPD%	0.352 0.318 0.327	Upper layer comfort	A: CA B: CA C: CA	0.364 0.194 0.139	Distal posterior thigh left region(DL)
	Upper layer discomfort	A: Force B: VA C: Load	-0.161 0.302 0.236	Upper layer discomfort	A: CA B: VA C: SPD%	-0.136 0.318 0.364	
	Lower layer comfort	A: VA B: CA C: Load	0.308 0.354 0.158	Lower layer comfort	A: Force B: CA C: Force	0.384 0.267 0.121	
	Lower layer discomfort	A: Mean B: CA C: CA	-0.185 -0.219 -0.231	Lower layer discomfort	A: Force B: Load C: SPD%	-0.194 0.26 -0.239	

Table 3.10 Highest correlations (25 AVCs≥0.3) in buttock right, buttock left, proximal posterior thigh right, proximal posterior thigh left, distal posterior thigh right and distal posterior thigh left regions (6B) divided based on crotch location on different layers of three cushions (CA: contact area, VA: variance, CV: coefficient of variation, SPD%: seat pressure distribution percentage)

Buttock right region(BR)	Upper layer comfort	A: Force B: Mean C: CV	0.376 -0.229 0.251	Upper layer comfort	A: SPD% B: Force C: Peak	0.264 0.453 0.13	Buttock left region(BL)
	Upper layer discomfort	A: Load B: Mean C: Load	0.234 0.161 0.278	Upper layer discomfort	A: Load B: Force C: Mean	0.471 -0.144 -0.138	
	Lower layer comfort	A: Force B: CA C: Force	0.403 0.328 0.422	Lower layer comfort	A: Mean B: CA C: CA	0.196 0.398 0.309	
	Lower layer discomfort	A: Force B: CV C: Mean	-0.102 0.357 0.313	Lower layer discomfort	A: CV B: CA C: Force	0.274 -0.135 -0.127	
Proximal posterior thigh right region(PR)	Upper layer comfort	A: Force B: Load C: Force	0.158 -0.249 0.115	Upper layer comfort	A:- B: Load C: -	- -0.131 -	Proximal posterior thigh left region(PL)
	Upper layer discomfort	A: Force B: Mean C: SPD%	-0.327 0.36 0.289	Upper layer discomfort	A: Force B: Mean C: VA	-0.113 0.307 0.269	
	Lower layer comfort	A: Mean B: CV C: Load	0.255 -0.321 -0.286	Lower layer comfort	A: Mean B: Mean C: CA	0.283 0.349 -0.273	
	Lower layer discomfort	A: Force B: VA C: CV	-0.358 0.266 0.34	Lower layer discomfort	A: Mean B: - C: Mean	-0.168 - -0.161	
Distal posterior thigh right region(DR)	Upper layer comfort	A: Mean B: Load C: Mean	-0.235 -0.232 -0.235	Upper layer comfort	A: CV B: Force C: CV	0.26 -0.204 0.26	Distal posterior thigh left region(DL)
	Upper layer discomfort	A: CA B: VA C: CA	-0.286 0.402 -0.222	Upper layer discomfort	A: CV B: VA C: CA	0.227 0.352 -0.14	
	Lower layer comfort	A: Mean B: CA C: VA	0.213 -0.35 0.435	Lower layer comfort	A: Mean B: Mean C: Mean	0.302 0.419 0.353	
	Lower layer discomfort	A: Force B: Peak C: VA	-0.338 -0.151 -0.296	Lower layer discomfort	A: VA B: Peak C: Mean	-0.209 -0.231 -0.285	

Discussion

In this study, we tried to explore the relationships between the perceived comfort/discomfort and different measures in different divisions of the pressure maps, which were collected on the top as well as at the bottom of three different cushions. We synthesized 4 postures in comfort evaluation and calculating pressure map measures. And a new division method (6B) was proposed based on landmarks as well as the knowledge that the proximal and distal posterior thigh has different sensitivity regarding the same load [43,158].

The proposed division method

Comparing method 4B and 6B, in which the only difference is whether the distal posterior thigh is separated, the number of measures with AVCs $\geqslant 0.3$ in the thigh area and the distal posterior area are the same on the bottom layer. The high correlation values in the distal posterior thigh (Region 5, 6 in division 6A and 6B) also affirmed the findings. This is also in accordance with the work of Vink and Lips [159] who concluded the feeling in the distal posterior thigh of both legs are essential as the sensitivity of the lower thigh parts are significantly higher than other parts touching the seat pan, most probably due to that in this area the blood vessels and nerves are ‘unprotected’ and soft tissue can be easily deformed.

In this study, the highest value of correlation showed up in the left buttock area of 4B and 6B methods. This is in accordance with Kyung and Nussbaum [151]. In their study, the pressure map of a driver seat cushion was divided using method 4A. The correlations between 39 pressure measures (including different regions on seat pan and backrest) of the driver seat cushion and whole-body comfort rating were calculated. The ratio between average regional pressure of left buttock and average total pressure had the largest correlations with comfort. Zhao et al. [153] also used the method 4A in their study and the highest correlation they achieved in their study is 0.307, which is between the peak pressure of left thigh region and the subjective ratings. Both works from Kyung and Nussbaum [151] and Zhao et al. [153] found the highest correlations in regions on the left. Similarly, more correlations with AVCs $\geqslant 0.3$ were found on the left in this study with methods 4A, 4B, 6A and 6B. The consistency may indicate that maybe because of 90% of population are right hand dominant, humans tend to put more weight on the left part of the seat. This could explain more correlations with discomfort. Another research studied the correlations between global pressure measures and regional comfort [160], in which the driver seat pan pressure map was divided equally into three regions (3B). Values of the correlations varied from -0.426 to 0.253, which is comparable to our study.

Top and bottom pressure maps

Comparing the pressure map of the top to the bottom, the regions with high correlation values differ. The foam cushion dissipates the weight of the user towards the seat pan [161], resulting in a larger contact area, less mean pressure values and less noise at the bottom pressure map. The force applied by the distal posterior thigh is not large, therefore not prominent in the pressure map at the bottom. For instance, with the 6A division method, 7 AVCs $\geqslant 0.3$ measures in the distal posterior thigh area were found on the top layer while only 3 AVCs $\geqslant 0.3$ were found in the same area on the bottom layer. When the pressure map is divided uniformly, the performance on the bottom layer decreased as the number of regions grow. Dividing the pressure map base on the location of the crotch can solve this problem since the anatomy of human being can still be reflected on the map. For instance, using the 6B division, there are 2 AVCs $\geqslant 0.3$ measures in the distal posterior thigh area, 3 in the proximal posterior thigh on the top map, for the bottom, the numbers are 6 and 4. Also, the measures of bottom pressure map had larger correlation values to comfort than discomfort. This finding indicates the potential of using pressure maps collected from the bottom of a cushion for long-term comfort studies, as in this spatial configuration, the materials of the pressure sensing mats will probably not influence the comfort experience of users as users will 'feel' the normal upholstery and the foam might allow moisture to pass through. Additionally, it might be that the bottom pressure mat had smaller peak pressure values and is less sensitive to unexpected damages.

Measures of the pressure maps

The largest correlation between pressure map measures and comfort/discomfort is the load with a value of 0.471, which show up in the left buttock area in 4B and 6B. The absolute value is comparable to the study of Fang et al. [160], in which 28 correlations with values between −0.426 to 0.253 were found between pressure parameters and comfort (overall and regional) in a driver seat. In general, CA (31 time > 0.3), Force (23 times > 0.3), and Mean (17 times > 0.3) are the most prominent measures. This is in accordance with findings of Naddeo et al. [150], and Li et al. [128]. However, in study done by Zhao et al. [153], the highest correlation was found between the peak pressure of left thigh and overall discomfort. This could be an indication that using single pressure parameter for comfort and discomfort evaluation might not be sufficient. The fluctuating performance of individual measures regarding different stiffnesses of the cushions implies that synthesizing multiple measures in predicting comfort/discomfort can be an important topic to study in future research.

Pressure measurement vs (dis)comfort

The pressure distribution is essential for studying both comfort and discomfort of the aircraft seats. Many AVCs $\geqslant 0.3$ measures were found between the recordings and discomfort, which is in accordance with the literature [104,151,153]. However, more AVCs $\geqslant 0.3$ measures between the recordings and comfort, especially on the bottom layer, were found which is in accordance with the work of Vink and Hallbeck [10] that physical aspects are still an important construct of comfort. Moderate correlations were found between (dis)comfort and pressure parameters, which is in accordance with previous studies [128,153,160]. These findings highlight the importance of pressure distribution in studying comfort. On the other side, comfort has a multifactorial construct [11] and objective measurements on other factors such as anthropometry, heart rate variability, electromyography and skin temperature can also reflect comfort of the subjects [24]. A proper integration of different measurements is recommended for a better understanding of sitting (dis)comfort.

Limitations

The population age of this study is between 23 and 37. Children, young persons and older adults were not included. Also, the sitting time was short and it is known that sitting longer increases discomfort (e.g. [125]) and higher correlations over time might have been found. However, it is difficult to evaluate the long-term comfort of a cushion with a pressure mat on the top, which is also a support for using pressure mats under the cushion. The thickness of cushions used in this study were 6 cm. The results might change if cushions with different thickness and hardness are used. Also, the seat pan that was used was relatively flat, which was needed because of the bottom pressure mat. A pressure mat can also not be curved that much as it creates a pressure value just by bending the material, which we wanted to avoid. A curved seat pan might have different comfort experiences, but was not used, which might be a limitation as well. Besides, the study focused on aircraft seats which limited the possibility of movement and made generalization to other areas limited.

Conclusion

In this study, we explored the comfort/discomfort experience regarding different divisions and measures of pressure maps collected on both the top and bottom of three different cushions. Based on literature, a new division method based on the location of the crotch point to divide buttock, proximal and distal posterior thigh on both sides was explored. This six-region division of the pressure map gives more information, especially on the bottom layer which shows a potential for further use in comfort studies. Among all the regions, pressure measures under the distal posterior thigh area have strong relationships with comfort and discomfort, especially the relationship with comfort on the bottom layer. For the area around the ischial tuberosity, pressure maps collected under the cushion seem to give more information related to comfort/discomfort, which highlights the potential of using this spatial configuration for long-term comfort studies.

Ethical statement

The experiment setup and the protocol were approved by the Human Research Ethical Committee (HREC) of Delft University of Technology under file number 1228. Consent forms were signed by all the subjects.

Acknowledgement

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Comfort wearables for in-flight sitting posture recognition

Abstract

Wearables are used to recognize human activities in various applications. However, there is limited evidence on the comfort feelings in using wearables, which is crucial for the adoption and long-term engagement of users in those applications. In this paper, we propose the concept of comfort wearables in the context of in-flight posture recognition. A comfort wearable and a tight-fit version, using identical hardware and software architecture, were prototyped and tested by 35 participants in a Boeing 737 cabin. During the usage of each wearable, participants were asked to perform seven frequently observed in-flight sitting postures and report their overall comfort/discomfort afterwards. A multilayer perceptron neural network was used to classify those activities. Experiment results indicated that participants appreciated the comfort wearable, rating it with significantly higher comfort scores and lower discomfort scores. Cross-validation results also revealed that using the comfort wearable achieved even better accuracy (74.8%) than using the tight-fit wearable (65.8%) in posture recognition. Outcomes of the study demonstrate that ergonomic design and technical accuracy are not competing factors in the wearable design and highlight the opportunities for designing and using comfort wearables in broader contexts.

Keywords: Losse-fit, Tight-fit, Ergonomics, Accelerometer, IMU, Wearability

Introduction

Posture recognition, as part of human activity recognition (HAR), holds a crucial role in decoding human behaviour. Its significance lies in uncovering how individuals interact with their environment during various task [162,163]. For instance, research has shown that human body posture is one of the most important factors in determining seating comfort [164], and frequently changing of postures often indicates the development of discomfort in ergonomics studies [24,40]. Another example is that researchers demonstrated that mental fatigue can be inferred based on body postures using the XSENS motion tracking system [165].

Human postures can be recognized based on sensors deployed in the environment. For instance, Wu et al. [166] used Intel® RealSense® to track the position of human joints and inferred hand postures accordingly. Cao and Liang [167] successfully recognized different postures of badminton players with a 90% accuracy based on captured videos and a self-developed Deep Convolutional Neural Network (DCNN). Besides cameras, pressure sensors are also frequently used in sitting posture recognition [168,169]. In the study conducted by Wan et al. [170], 32x32 pressure sensors were placed on the top surface of the office chair cushion in a grid setup, and 12 sitting postures were recognized with an accuracy of 89.6% using Support Vector Machine (SVM). Liang et al. [171] also designed a smart cushion with pressure sensors integrated and achieved an accuracy of 98% in classifying 15 sitting postures.

Though using information provided by sensors in the environment for posture recognition is effective, it is always context dependent. Using wearable sensors can mitigate this constraint [172–174]. For instance, Tian et al. [175] used data collected from a smart watch to recognize activities including standing, walking, running, upstairs, and downstairs. Fujiwara et al. [176] recognized hand postures with a mobile phone equipped on the forearm.

Many sensors can be embedded in wearables, which are worn on the body to monitor and classify different human activities in real time. For instance, Kim et al. [177] used a capacitive belt sensor placed around the fourth thoracic vertebrae to detect user daily activities with an accuracy of 74%-85%. Among different types of sensors, accelerometers and Inertia Measurement Units (IMUs, incl. accelerometers, gyroscopes and sometimes compasses) are often used in wearables for recognizing human body postures. Forsman et al. [178] found that both accelerometers and IMUs can be used to detect 4 postures and 24 types of movements based on experiments with 38 warehouse workers. Commercial products, such as XSENS [179], are often used in posture recognition. Besides, researchers also developed new types of wearables, e.g. Yan and Ou attached IMUs to the belt for fall detection [180]. Fusing information from different types of sensors might improve the accuracy, e.g. besides IMUs on the belt, Tan et al. [181] achieved an accuracy of over 98% for fall detection by integrating data from pressure sensors under the feet.

Wearables can be affixed to various parts of the human body. Depending on the level of attachment, we classify these attachment methods as either comfort/loose-fit wearables or tight-fit wearables. In tight-fit wearables, such as a smart wristwatch, the connection between the sensor and the body part remains fixed. However, in comfort wearables, such as a mobile phone in the pocket of a jacket, the attachment may not be fixed. Table 1 provides some recent studies on posture recognition utilizing different wearable designs, wherein sensors are attached to the users' torso.

The wearability [182], personalization, functionality and integration are four key factors in establishing customers' initial trust in wearables [174,183]. The comfort of wearables, which is closely associated with wearability and personalization, can be a decisive factor in users' long-term adoption, e.g., monitoring postures of users during the day to prevent musculoskeletal disorders and improve overall health. However, as shown in Table 3.11, most wearables for posture recognition are tight-fit wearables and only a few are comfort wearables, e.g. Farnan et al. [184] attached 9 magnets to a comfort/loose-fit t-shirt for sitting posture recognition when working from home. Mattmann et al. [185] tried a comfort/loose-fit design with 6 ECG sensors for recognizing postures of drivers. Both studies confirmed the possibilities of using comfort wearables for posture recognition, but the accuracy was not given. The question “Is it possible to recognize postures with comfort wearables?” and “How to evaluate the comfortable feeling of wearables for posture recognition?” remain to be answered.

In this paper, we present the design and validation of a wearables, named Jacket, for posture recognition during air travel. Our scientific contributions are:

1. We developed two types of wearables, one optimized for comfort and the other for a tight-fit, utilizing identical hardware and software for inflight posture recognition.
2. Alongside accuracy, we incorporated subjective comfort ratings as a measure to evaluate the performance of the wearables.
3. We validated that properly sized comfort wearables received significantly higher comfort ratings and achieved comparable, if not slightly higher, accuracy for posture recognition compared to tight-fit wearables.

Table 3.11 Literature studying trunk movements.

Context of the literature	Wearable Setup	Tight or Loose	No. subjects	Postures / activities	Classifier	Acc
Posturers of construction workers [186]	IMUs attached to head, chest, arm, thigh, and calf.	T	9	Overhead, bend, walk, stand.	DNN	81.2%
Postures in table tennis [187]	An IMU attached to wrist.	T	6	Hits and misses	Decision tree	95%
Sitting postures of working from home [184]	A shirt with 3*3 magnets placed above the sternum.	L	N/A	Lean left, right, forward and backward spinal postures.	N/A	N/A
Head postures [188]	Three IMUs placed around neck	T	3	Sitting: relaxing, reading book, using laptop, using mobile phone, watching videos; Standing: up, using a mobile phone; walking;	Decision extra tree	96.78%
Postures in daily activities [177]	A capacitive belt placed around chest (T4 position)	T	7	Supine with neutral head position; standing; sitting; side lying; supine with 45° cervical flexion; supine with 45° cervical extension.	Probability analysis	74%-85%
Daily sitting and standing postures[189]	IMUs at skin around the area of neck, upper back and lower back	T	7	Sit straight, back rested on chair, hands on the lap; sit straight, neck flexed down, hands on the lap; sit with rounded back, head close to table, hands on table; forward head posture, hands on able; sit deeper inside the chair, arms on the armrest, shoulder up, leg spread out; stand straight; stand with forward head posture, hands on the sides; stand swayed backwards, hands rounded in front; stand with right shoulder up, left shoulder down, body weight on right leg.	Random forest	95.68%
Swimming postures [190]	A module with IMU integrated attached to lumbar area	T	2	Different swimming styles including butterfly, breaststroke, freestyle and back crawl.	HMM	Over 90%
Posture correction and training [191]	IMU at the back of shoulder	T	4	Proper standing; proper sitting; proper exercise postures such as plank, superman, squat, side plank, etc.	N/A	N/A
Postures of daily life [192]	UCI Machine-Learning repository	N/A	4	Sitting; standing; walking; standing up; sitting down.	Random forest	Over 95%
Sitting posture	Two IMUs at back along spine.	T	N/A	Spine bending angles	N/A	N/A

monitor and correction [193]						
Postures of daily activities [194]	An elastic t-shirt with inductors on the front and back along spine.	T	4	Sitting on a stool, flexion-extension of the trunk; Sitting on a chair, bending-stretching forward of the trunk, hands resting on a table and return; Sitting on an armchair with trunk extended.	N/A	Correlation over 0.95
Driving postures [195]	A comfort/loose-fit t-shirt with 6 ECG sensors (2 in front along the safety belt, 4 at lower back)	L	10	Safety belt fastened: forward, on back, right, left; no seat belt: on back, others.	N/A	N/A
Postures of daily activities [185]	A tight-fit clothing with 21 strain sensors integrated into elastic textile on the back.	T	8	Sitting: upright, slumped, with rotation of trunk(right, left); bending trunk sidewards (right, left); lifting shoulders(right, left, both); arms to the front, sides and overhead; Standing: upright; with rotation of trunk(right, left); bending trunks sidewards (right, left); both shoulder lifted; slumped; bending trunk maximally forward; extending arms to the front; standing while squatted; with flexing torso sidewards (right, left).	Naive Bayes	84%

Design of comfort and tight-fit wearables

The framework of the approach

Figure 3.4 presents the overall approach of the study. Participants were asked to perform a set of identified postures during the flight in an aircraft seat. The tight-fit and the comfort wearables are used to collect data. The sensor configurations of the two wearables are the same: two accelerometers on the shoulders and two IMUs on the waist. The procedure of the proposed posture recognition method contains two major steps. Initially, data captured by different sensors were aligned to guarantee the inner relationship between the sensor data and the corresponding posture. Then the Multilayer Perceptron (MLP) classifier was used to predict the posture category based on the aligned sensor information.

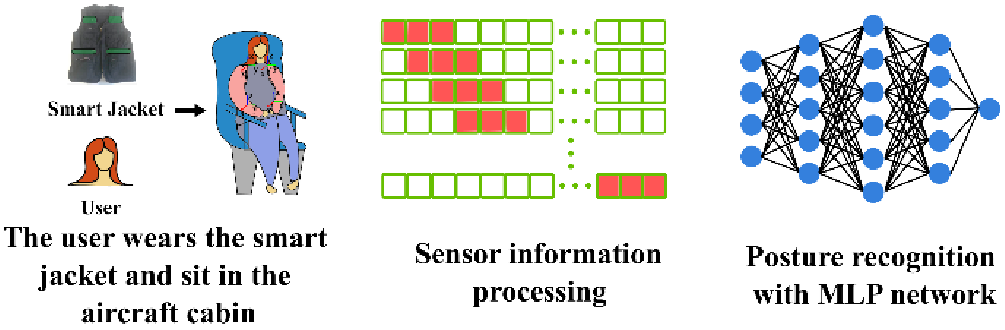


Figure 3.4 Framework of the approach

Hardware

Figure 3.5 presents the block diagram of the hardware setup of the Jacket. It comprises two accelerometers (ADXL355), each capable of recording acceleration in the x, y, and z directions; two IMUs (FXOS8700 + FXAS21002), each capable of recording acceleration in the x, y, and z directions along with rotations in the yaw, roll, and pitch; a Raspberry Pi 3A+ controller; and a 3000mAH Li-polymer Battery HAT, which can power the system for approximately 4 hours. A self-developed Python script was created to capture these 18 features from the four sensors at a frequency of approximately 15~30 HZ.

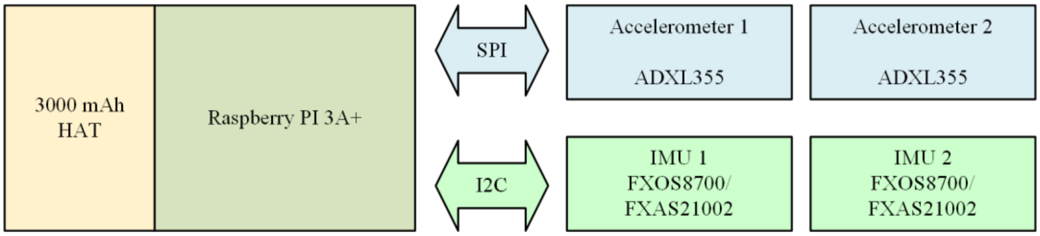
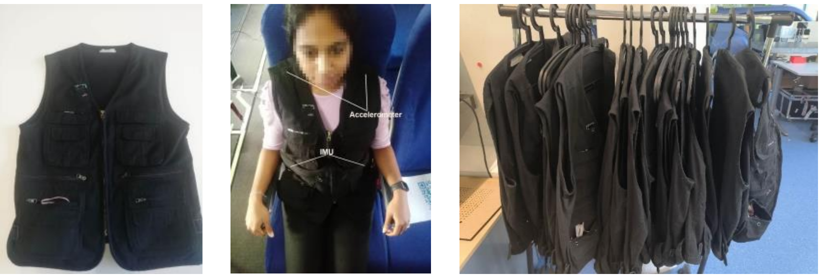


Figure 3.5 Block diagram of the hardware setup.

Using the proposed hardware, we designed comfort wearables based on a vest made of cotton denim (Figure 3.6a). Two accelerometers were sewn onto the inner side of the left and right shoulders, respectively. Two IMUs were positioned around the waist, just above the two pockets.

The battery was stacked on the Raspberry Pi 3A+ and positioned in the right pocket of the cotton denim. To minimize the impact of the vest on perceived comfort, soft fabric was used to cover all the wires and sensors, ensuring that users would not feel them, as shown in Figure 3.6b. Twenty vests with four different sizes were created for users with varying anthropometric measures, as depicted in Figure 3.6c. Sizes of the vest can be found in Table 3.12.



(a)The comfort wearables.

(b) The participant wears the comfort wearable (size L).

(c) Comfort wearable with different sizes.

Figure 3.6 Comfort wearables.

Table 3.12 dimensions of different sizes of comfort wearables.

Size	L	XL	XXL	XXXL
Chest circumference (cm)	**96**	**102**	**108**	**114**
Length(cm)	**63**	**64**	**65**	**66**

As a comparison, we also created a tight-fit version of the wearable with the same sensors, as shown in Figure 3.7. To ensure the tight fit, we designed the wearables based on an elastic undershirt, as seen in Figure 3.7a. The dimensions of the undershirt were selected in such a way that it is able to fit the P5 to P95 populations due to its elasticity. Sensors are fixed onto the undershirt, as illustrated in Figure 3.7b, and in Figure 3.7c, a user (around P50) is shown wearing it.

(a) The dimension of the tight-fit wearable.

(b) The tight-fit wearables.

(c) A participant wears the tight-fit wearable.

Figure 3.7 Tight-fit wearables.

Posture classification

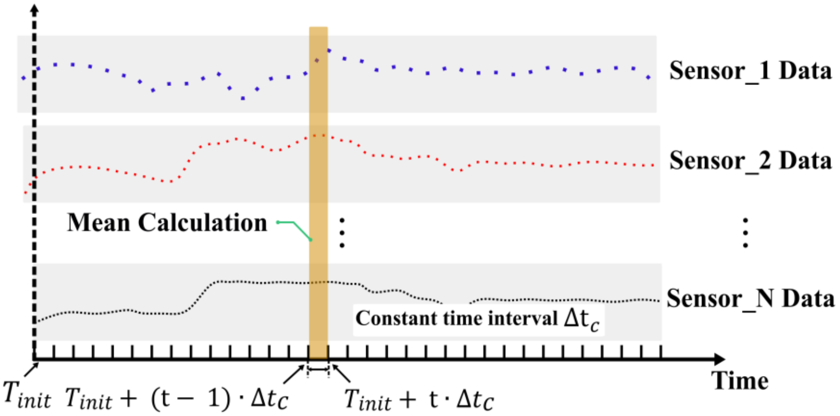


Figure 3.8 Time alignment of different sensors.

Data $\{D_n | n = 1 \ldots N\}$ captured from 2 accelerometers and 2 IMUs were synchronized first. In this paper, $N = 18$, representing 18 features mentioned in previous section. Taking $D_n = \left\{D_n^{t_n^1}, D_n^{t_n^2}, \ldots, D_n^{t_n^i}, \ldots, D_n^{t_n^T}\right\}$ as the data of the n^{th} feature where $D_n^{t_n^i}$ means the data captured at timestamp t_n^i, we firstly down sampled all captured data to a synchronized initial timestamp T_{init} and a constant resampling frequency F_c. T_{init} was specified as:

$$T_{init} = argmax_{1 \ldots N}\{t_n^1 | n = 1,2,\ldots,18\} \qquad (1)$$

and

$$F_c < argmin_{1 \ldots N}(F_n | n = 1,2,\ldots,18) \qquad (2)$$

where F_n is the frequency of D_n.

The resampled data for different features can be denoted as $\{DS_1, \ldots, DS_n, \ldots, DS_N\}$. Each resampled the time series data of a certain is denoted as $\{DS_n | DS_n = (DS_n^1, \cdots, DS_n^t, \cdots, DS_n^T)\}$, where

$$DS_n^t = \frac{\sum_{j=1}^{N_n^t} D_n^j}{N_n^t} \qquad (3)$$

Here n is the index of the feature, T is the number samples and the time interval between consecutive records $\Delta t_c = {}^{1}/_{F_c}$. Besides, $D_n^j = \{D_n^{t_n^i} | T_{init} + (t - 1) \cdot \Delta t_c \leq t_n^i \leq (T_{init} + t \cdot \Delta t_c)\}$, N_n^t is the number of records D_n^j, as shown in Figure 3.8. In practice, we used 30 seconds time span for posture recognition, therefore $T = 30/\Delta t_c$.

To reduce the noise in the original data, we employed the rolling window method to pre-process each DS_n as shown at the left of Figure 3.9. Given the aligned resampled data $\{DS_1, \ldots, DS_n, \ldots, DS_N\}$, at each timestamp t, a multi-dimension vector $\{s_t | s_t = [DS_1^t, DS_2^t, \cdots, DS_n^t, \cdots, DS_N^t]\}$ that represents all sensor features was acquired. Using the rolling window method, the output $\{M_t \,| M_t = (A_1^t, A_2^t, \cdots, A_n^t, \cdots, A^t{}_N)\}$ for posture recognition was calculated as the mean value of the data inside the window length L:

$$A_n^t = \frac{\sum_{g=1}^{N_G} s_g}{N_G} \tag{4}$$

where N_G represents the number of features of s_t between t and $(t + L)$.

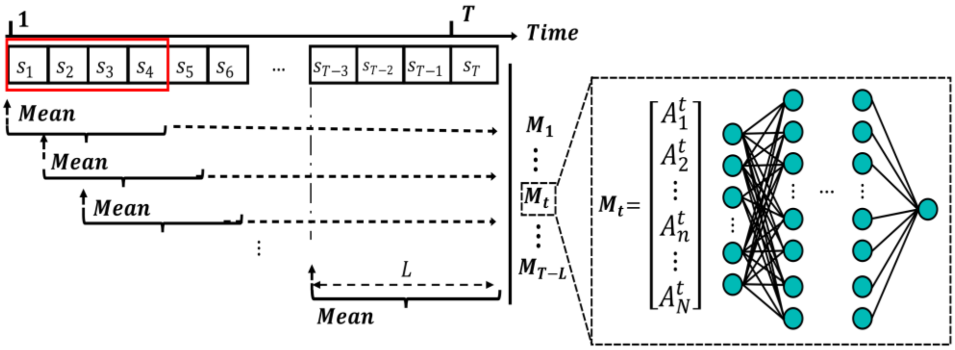


Figure 3.9 Data processing and classifier.

MLP classifier [196] was adopted for posture recognition as shown in the right side of Figure 3.9. M_t was used as the input of the MLP classifier, followed by two hidden layers, each with 100 neurons. The output layer had only one node that represents the corresponding posture category. The one-vs-rest (OvR) strategy was adopted to improve prediction accuracy. For each posture, a specific MLP was trained for this category against all the other postures. Therefore, the number of MLPs for posture prediction would be the same as the number of postures to be predicted.

Experiments setup

Posture selection

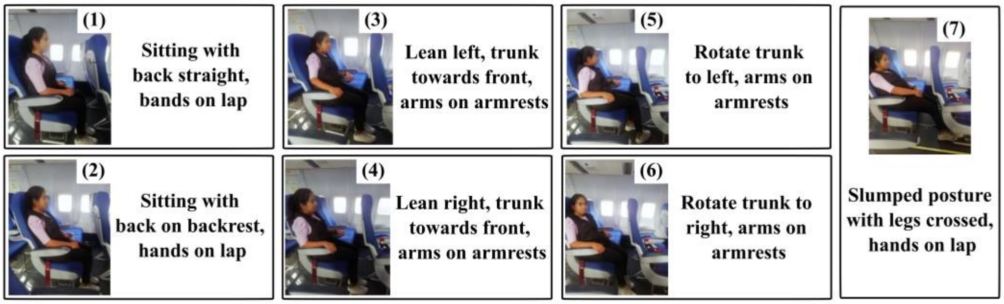


Table 3.10 Inflight sitting postures used in this study.

According to work of Liu et al. [28], the most frequently observed posture (29.7%) among passengers is sitting with the back against the backrest, both feet uncrossed on the floor and hands on the lap. Three other similar postures with different arm and head positions account for 29.1% in total. Another sitting posture mentioned as one of the most common postures is sitting straight with both feet uncrossed on the ground and hands on the lap. Slumped postures with feet/legs crossed constitute 8.8% of the observed postures. The remaining most common postures are all with the back against the backrest and feet/legs crossed. However, it was not clear which leg was on the top and which arm was performing tasks. Tan et al. [197] mentioned the body side of performing different postures in their study of sleeping postures in the economy class of an aircraft. They found that people recline to one side and use the armrest to support their body, sometimes also with rotation of their torsos so they also get support from the backrest. Using this knowledge, seven postures as Figure 3.10 were chosen for this study as the task for the participants.

Participants

Table 3.13 Size of each participant.

Participant No.	Age	Gender	Stature(cm)	Weight(kg)	BMI	Comfort wearable size
1	30	f	166.3	61.9	22.4	L
2	27	f	162.3	53.3	20.2	L
3	27	m	164	64.3	23.9	L
4	28	f	158.2	66.5	26.6	XXL
5	31	m	172.2	69.7	23.5	L
6	29	f	175.5	58.9	19.1	L
7	32	m	173	67.4	22.5	L
8	30	f	165.5	62.4	22.8	L
9	25	m	173	58.8	19.6	L
10	27	f	169.5	55.8	19.4	L
11	26	f	170.5	61.6	21.2	L
12	30	f	163.4	62.7	23.5	XL
13	27	m	165.7	39.1	14.2	L
14	28	f	154.5	50.8	21.3	L
15	27	f	165	53.6	19.7	L
16	34	f	159	53.8	21.3	L
17	24	m	176.5	72.1	23.1	L
18	24	m	170	67	23.2	L
19	24	m	163	58.9	22.2	L
20	26	m	167.8	64.2	22.8	L
21	40	f	160	61.1	23.9	XL
22	22	m	182.5	85	25.5	XL
23	30	m	167.5	85.8	30.6	XXXL
24	24	f	158.5	51.5	20.5	L
25	29	f	152	51.8	22.4	L
26	34	m	175.5	72.2	23.4	L
27	28	m	158	47.9	19.2	L
28	29	f	165.5	72.7	26.5	XXL
29	27	f	165.2	58.6	21.5	L
30	34	m	173.5	89.1	29.6	XXXL
31	24	f	154	57.1	24.1	XL
32	25	f	164.5	58.9	21.8	L
33	30	m	178.2	90.9	28.6	XXXL
34	24	m	179	73.9	23.1	L
35	31	m	174	70.2	23.2	L

To explore the use of comfort wearables for inflight sitting posture recognition, an experiment was conducted in a Boeing 737 aircraft cabin. In total 35 subjects from the Netherlands, Germany, China, India, Thailand, Italy and Brazil participated in this study. Their ages varied between 22 to 40 years old. In the experiment, participants were allowed to select the most suitable size of the comfort wearables. Detailed information about participants can be found in Table 3.13.

The mean height of males is 171.3 cm and for females, it is 162.7cm. As a comparison, the mean heights of the European population are 175.8 cm and 163.5 cm for men and women, respectively [198]. Regarding the sample size, G*Power calculation indicated that for medium to large effects (0.6), the sample size is able to achieve a power of 0.95. For the representativeness of the subjects in the population, the specificity [196] of the subjects in this study regarding the European population [198] is 0.002.

Protocols

After a short explanation and collection of consent forms, participants put on the wearables. They had about 10 minutes to get used to the wearable before the data collection started, during which they were asked to perform the postures as shown in Figure 3.10. Each posture took approximately 1 minute. Regarding the sequence of two types of wearables, 18 subjects started with the tight-fit wearable and the remaining participants started with the comfort wearable. After performing all the postures in a wearable, they evaluated the overall comfort and discomfort from 0 (no comfort/discomfort) to 10 (extreme comfort/discomfort) using the comfort/discomfort questionnaire [154].

Experiment Results

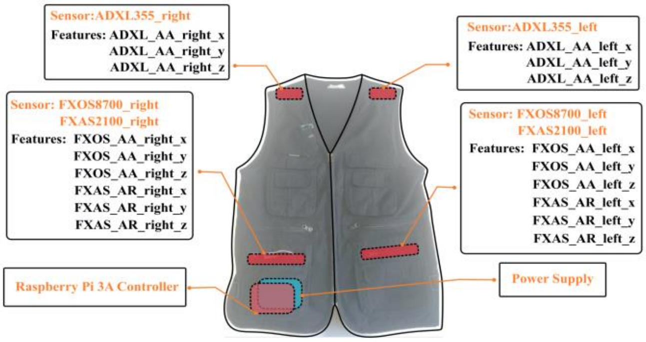


Figure 3.11 The features captured by each sensor and the assembling position of each sensor on the comfort wearable. The same features are captured on the tight-fit wearable, and the sensors are assembled on similar positions.

18 features on the torso movements were captured using sensors embedded in the wearable for posture prediction. The four sensors are symmetrically distributed from left to right with the zipper as the centre as Figure 3.11. On the left side, the features captured by the ADXL355_left were 3D accelerations. Another three acceleration features were captured by the FXOS8700_left sensor. The features measured by the integrated FXAS2100_left sensor were 3D angular velocities. Same

features were captured by the sensor on the right. Information captured by the compass was not used in this study due to: 1) the plane might turn slightly while users are sitting still; 2) there is a potential presence of products made of ferrite materials.

Posture recognition accuracy

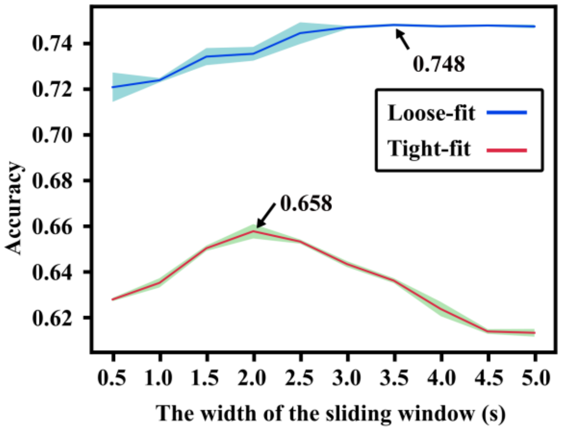
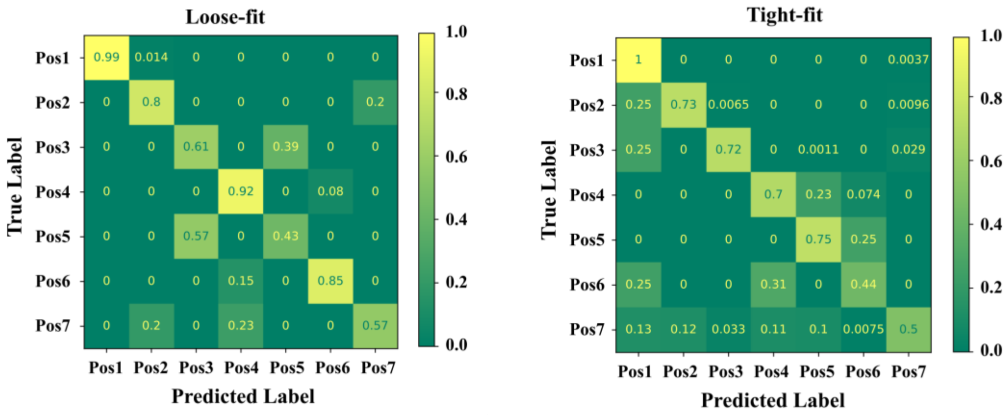


Figure 3.12 Posture recognition accuracy of the comfort/loose-fit and tight-fit wearables with the increment of the sliding window length.

Figure 3.12 presents the posture recognition accuracies of the comfort/loose-fit and tight-fit wearables under different sliding window widths, which were adjusted from 0.5s to 5s with a 0.5s interval. For each experiment, the network was trained and tested using the 10-fold cross-validation method, and the average prediction accuracy was taken as the result. As illustrated in Figure 3.12, the posture recognition accuracy based on the data captured with the comfort/loose-fit wearable was always higher than the accuracy of the tight-fit wearable. For different sliding window widths, all accuracies of using the loose-fit wearable were higher than 72%. On the contrary, the highest accuracy of using the tight-fit wearable was about 65.8%. Overall, with the increment of the sliding window width, the accuracy of the loose-fit wearable presented an upward trend with a few fluctuations around 74% when the width was larger than 2.5s. The highest accuracy of recognition using the loose-fit wearable was 74.8% when the width of the sliding window was 3.5s.

The confusion matrix of the network with the best prediction accuracy for posture recognition with the comfort/loose-fit (74.8% accuracy when the sliding window width was 3.5s) and tight-fit wearables (65.8% accuracy when the sliding window width was 2.0s) are given in Figure 3.13(a) and Figure 3.13(b), respectively. The seven postures explained above are denoted as Pos1, Pos2, …, and Pos7. For posture recognition with the loose-fit wearable, the accuracies of recognizing Pos1, Pos2, Pos4 and Pos6 reach over 80%. The lower accuracies were observed for Pos3, Pos5 and Pos7. For the tight-fit wearable, Pos1 was successively recognized with an accuracy of around 100%. Pos2, Pos3, Pos4, Pos5 can also be identified with over 70% accuracies. Low accuracy appeared in classifying Pos6 and Pos7. Nearly 56% of posture data of Pos6 was misidentified.



(a) (b)

Figure 3.13 Confusion matrix of comfort/loose-fit (a) and tight-fit(b).

Sensor contribution

18 features were used for posture recognition, and the contribution of each feature regarding the posture recognition accuracy was evaluated using the Shapley (SHAP) values [199]. Figure 3.14 illustrates the sorted mean SHAP value of each feature, which represents the average influence of each feature on the output of the model, for the loose-fit wearable, and the associated SHAP value for the tight-fit wearable is given as well. The accelerometer data contributed most for both the comfort/loose-fit and tight-fit wearables. It can be noticed that accelerometers on the waist (FXOS8700) contribute more than the sensors on the shoulders (ADXL355). The contribution of accelerometers on the waist and shoulders of the tight-fit wearable were nearly the same regarding the comfort/loose-fit wearable.

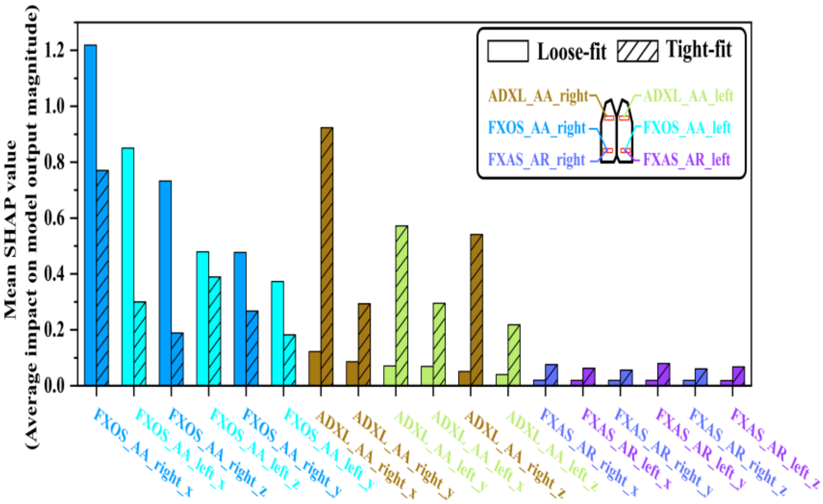


Figure 3.14 The mean SHAP value of each feature for comfort/loose-fit and tight-fit wearables.

Comfort

The comfort data from one participant was excluded due to incompleteness. The normality of both comfort and discomfort ratings was checked. Since the data were not normally distributed, Wilcoxon Rank tests were used to compare perceived comfort and discomfort regarding different versions of wearables. To understand how body shapes could influence perceived (dis) comfort wearing different versions of wearables, Pearson correlations between body measurements and (dis)comfort scores wearing different wearables were calculated. The test population was divided into two groups based on the mean value of each body measurement.

Table 3.14 Comfort and discomfort scores(0-10) of the comfort/loose-fit wearable and the tight-fit wearable.

	Comfort/loose-fit version	Tight-fit version	P value
Comfort	4.00±1.26	3.50±1.33	0.002**
Discomfort	2.24±1.57	2.76±1.52	0.034*

Table 3.15 Correlations(p<=0.05) between different body measurements and perceived (dis)comfort of participants wearing both comfort/loose-fit and tight-fit wearables.

	age	**height**	**Weight**	**BMI**	**Hip width**	**Sitting depth**	**Popliteal height**
Comfort/loose-fit comfort			0.396	0.406		0.420	
Comfort/loose-fit discomfort	0.445						
Tight-fit comfort		0.353	0.465	0.379		0.424	0.348
Tight-fit discomfort			-0.384	-0.357			

The results of the comfort and discomfort scores of the two types of wearables are presented in Table 3.14. The loose-fit wearable was found to be significantly more comfortable and less uncomfortable compared to the tight-fit wearable. Table 3.15 presents the statistically significant correlations ($p<=0.05$) between different body measurements and perceived (dis)comfort in both wearables. In the tight-fit wearable, the body weight had the largest correlation with perceived comfort, which was 0.47. The tight-fit wearable had more significant correlations between body measurements and (dis)comfort than the loose-fit wearable. Regarding different anthropometric measures, the body weight could influence both comfort and discomfort of wearing the tight-fit wearable, while height and sitting depth only affected the comfort of wearing the tight-fit wearable.

Discussion

According to the findings, comfort/loose-fit wearables can achieve in-flight posture recognition with a better average accuracy than tight-fit wearables equipped with the same sensors. One possible reason for this is that the loose-fit wearable filters out noise during the data acquisition process by maintaining a small distance between the device and the human body. This distance enhancement increases recognition accuracy in certain postures, such as Pos 1 and Pos 4.

Another contributing factor is that the tight-fit wearable only achieved 44% and 50% accuracies in recognizing Pos 6 and 7, respectively, which adversely impacted its overall performance. However, both types of wearables encountered difficulties in recognizing Pos 7, the slumped position. This could be attributed to the specific cabin context of the aircraft, where subjects, especially those with a taller stature, often pressed their knees against the back of the front seats.

Moreover, postures involving rotation of the lower back posed challenges. The comfort/loose-fit wearable exhibited poor performance in detecting whether the participant's torso was rotated to the left. This could be due to the majority of participants being right-handed, resulting in greater flexibility on the right side. Consequently, the accelerometers on the shoulders, which were most effective for posture recognition during right-side rotation, significantly contributed to the performance of the comfort/loose-fit wearable.

Conversely, the tight-fit wearable exhibited less contribution to right-side torso movement, likely because the most effective sensors were located on the waist. Movement on the opposite side of the waist during body rotation might explain this observation. These distinctions highlight potential reasons for discomfort introduced by the tight-fit wearable, which constrained the movement of the subjects.

Classification method

The purpose of the proposed wearables is to identify static postures, and a few large fluctuations were observed in the data. The MLP method is selected due to its simplicity rather than the long short-term memory (LSTM) method. Nevertheless, it is inevitable to encounter sensor noises and human fidgeting while seated. To address this issue, the rolling window method was employed to mitigate the noise and improve the data quality. The MLP method was also adopted by Jang et al. [200] for pose recognition based on features captured from the wearable sensors. Compared to their posture recognition accuracy of 70.1%, which was achieved based only on accelerometers, our best result was slightly better with an accuracy of 74.8% based on the comfort/loose-fit wearable.

Position of sensors vs accuracy

Sensors were placed on the shoulders and near the waist for both the comfort/loose-fit wearable and its tight-fit version in sitting posture recognition. All the postures are common postures during flights and the variations between some postures can be very small. The required postures mainly involved thoracic and lumbar rotation, especially for Pos3, 4, 5, 6. Each vertebra is only able to rotate in a very limited range [201], e.g. Neumann indicated that the thoracic vertebra and lumbar vertebra can rotate only 3 degrees and 2 degrees respectively [202]. Besides, the contribution of accelerometers at different body parts varied between the two types of wearables. The comfort wearable relied mostly on accelerometers at the waist, while the tight-fit wearable utilized all available data in a more balanced manner. This might be caused by several reasons, e.g., in the use of comfort wearables, the friction force between the backrest and the jacket might influence the positions of the accelerometers on the shoulder, resulting in less accurate data collected at the shoulder. Meanwhile, the slightly higher accuracy of using the comfort wearables can be interpreted as that in most cases, the loose fit acts as a low pass filter regarding the movements of the human body, thus enhancing the quality of the signals.

Wearable performance and comfort

The comfort/loose-fit wearable proved to be significantly more comfortable than the tight-fit wearable. Wearing clothing that restricts movement can be uncomfortable [203], and the comfort/loose-fit wearable allowed for more freedom of movement compared to the tight-fit wearable. Additionally, the normal appearance of the comfort/loose-fit wearable contributes to a better experience in wearing, as social pressure and others' opinions can also influence how people feel and behave when wearing different types of wearables [204].

In the experiment, participants selected the size of comfort wearables at their wish. While all users appreciate the comfort of the comfort wearables, we did not find a significant difference between size and accuracy. This addresses the importance of wearability and personalization, as personalized fit introduces a better inclusiveness for different body shapes, enabling the wider adoption of wearables in daily activities [205].

Limitation

The ages of participants in this study were limited to the range of 22 to 40, therefore the effectiveness of the proposed method on other populations, e.g., the children and the elderly, needs to be verified. Furthermore, it is important to note that although the experiment was conducted in a Boeing 737 cabin, the aircraft itself was stationary and the vibrations caused by the operating engine were not taken into consideration during the study. Additionally, the study only examined wearables with motion sensors located on the shoulders and waist, and wearables with sensors located on other parts of the body require further investigation.

Conclusion

The study investigated the feasibility of utilizing comfort/loose-fit and tight-fit wearables for in-flight sitting posture recognition, employing an MLP-based classifier. Experiment results indicated that the comfort wearable achieved a recognition accuracy of 74.8%, surpassing the accuracy reached by the tight-fit wearable (65.8%). Furthermore, the comfort wearable was found to provide significantly higher levels of comfort and lower levels of discomfort compared to the tight-fit wearable. These findings suggest that comfort wearables can be considered as an option for posture recognition, as it reduced impact on comfort for subjects without scarifying the accuracy. Further research is needed to determine the appropriate level of looseness for different body parts in order to enhance recognition accuracy without compromising comfort.

Acknowledgments

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Ethical statement

The experiment protocol was approved by the Human Research Ethical Committee (HREC) of Delft University of Technology under the file number 1228. Consent forms were acquired from all participants.

4. Design application

This chapter is based on following paper:

1. Vicente AN, Yao X, Song Y & Vink P. Clear preference for a seat and almost no difference in comfort: the basics for further development of an aircraft seat. Accepted by International Comfort Congress, 2023.

Clear preference for a seat and almost no difference in comfort: the basics for further development of an aircraft seat

Abstract

Passenger space in long haul flights is limited, but by using the vertical space more personal space can be created. In this study a new concept of an aircraft seat making use of the vertical space in the aircraft cabin was tested. The research question is whether passengers see and experience the advantage and experience differences in comfort. To test the potential, 29 participants were asked to sit for 40 minutes in the new and in a traditional aircraft seat. Every 10 minutes they were asked to fill in a questionnaire regarding comfort and discomfort. The Wilcoxon signed-rank test ($p<.05$) was used to check differences of comfort and discomfort scores between different sitting conditions. Afterwards the participants were interviewed on their experience. Only a few significant differences in comfort or discomfort could be found. However, 76% of the 29 participants preferred the new seat and 90% see potential in this seat. It was preferred because of the extra space and the potential to sleep better. A clear preference of the new developed concept was shown. The research also shows that in testing a low-fidelity prototype, results of closed comfort questions provide limited information. On the contrary, answers of open questions and in interviews are essential to gather the users' opinion.

Keywords: aircraft interior, passenger experience, low-fidelity prototype

Introduction

Improving seat comfort in aircrafts is relevant as passengers' comfort is important to airlines, as it is one of the decisive factors for passengers to "fly again with same airline". Ahmadpour et al. [8] showed that seat comfort is one of the most influencing factors in overall passenger comfort. On the other hand the airline industry is a competitive market where passengers demand for comfort at a low price [93]. To keep the price low, airlines need to get as many passengers on the plane as possible at the expense of comfort. Bouwens [39] found that the top five of most important seat related elements were legroom, foot space, hygiene, the bottom cushion and overall space. Three of these five elements concern space. Some airlines try to create space by developing a thin backrest [206] and some have a curved seatback following the shape of the human body to allow the passenger who sits behind splays the legs a bit, as the knees will have a bit more room. Another possibility is to use the vertical space, which is not seen in flying aircrafts yet. This principle of developing a seat using vertical space is applied in the Flying V aircraft interior [207]. This seat concept was called the 'chaise longue'. In a study among 1692 participants it was shown that, the majority (36%) preferred this 'chaise longue' out of 4 types of seats [208]. This seat (see figure 4.1) uses the vertical space in the airplane and creates more legroom, more foot space and more overall space within the 32" seat pitch. This 'chaise longue' creates the potential to change the position of the human body more than in the current 32" pitch seats.

Figure 4.1 The first concept of “chaise longue” shown to 1692 participants of which 36% preferred this seat out of four choices.

Figure 4.1 is the first concept of the ‘chaise longue’ [209] and is made in a 1:1 mock-up and you could only look at it. Based on discussions with specialists improvements were made and this seat was further engineered. Renderings were made with solutions for various problems found in the first concept. The attachment on the ceiling was changed to fixation to the floor, in- and egress was solved by making the seat pan slide backwards (see figure 4.2), the recline was made possible up to 15 degrees in both the upper and lower row (larger recline angle than current 32” aircraft seats). Footsteps were made to get into the upper row and the neck rest was engineered (see figure 4.2).

Figure 4.2 The CAD model, upper left: an overview with mannequins, lower left: recline in the upper row, upper right: showing the sliding of the seat pan backwards, lower right: showing the neck rest and recline of the lower seat.

Based on the initial design, a mock-up was made with two upper row seats and two lower row seats (see figure 4.3). The idea was to have more reclined backrest angles in the upper seats and more leg stretching possibilities in the lower seats (see figure 4.3). The leg room was 1620mm deep (horizontal line from the backrest to next seat), 400 mm height at feet level and 432 mm wide. Compared with the mean functional leg length of 1105 mm (close to buttock- feet length seated) described by Hsiao et al. [210],this leaves enough space for the legs. After the verification, a concept prototype based on the CAD drawings was made (see figure 4.4). In the upper row a reclined and an upright backrest was produced. This was done in the lower row as well. Existing aircraft seat cushions for the seat pan and back rest were used to make the seat a bit more comfortable. The question on the kind of prototype to be used is determined by constraints like available time and budget [211]. In this case a reduced fidelity prototype was used as it is faster to build and more utilisable in earlier stages in the product development cycle. Sauer et al. warned that there are concerns that a low fidelity prototype may create a less accurate picture of actual user behaviour [211]. However, a complete design in a real context will be available in years from now and it is important to get an idea whether or not to continue with this project.

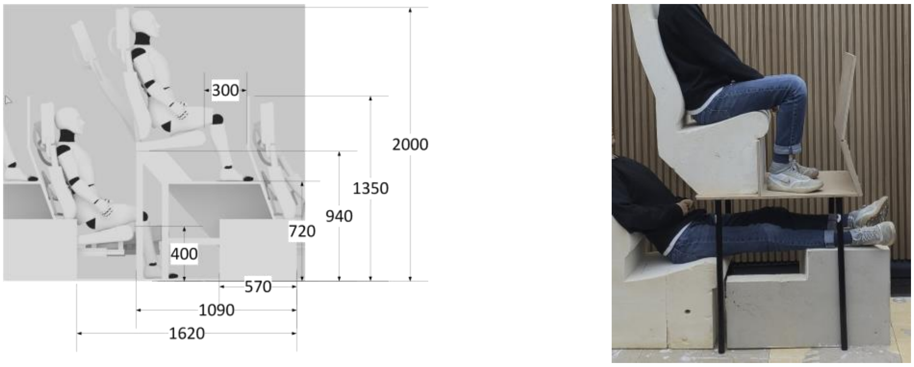

Figure 4.3 Study of leg stretching possibility in the lower seat (left: Dimensions(in mm), right: study on a mockup)

Figure 4.4 The chaise longue prototype used in this test

To check how passengers experience this completely new way of seating in an aircraft, a test was done. The research questions for this test are: 1) Is the ‘chaise longue’ using the vertical space in a new way preferred above a traditional aircraft seat positioned at 32” pitch? and 2) Is the comfort and discomfort improved by the chaise longue compared with a traditional aircraft seat positioned at 32”?

Method

To answer the research question, a method focusing on problem solving used in in design science research, has been used in this study [212]. In 2007, Hevner [213] proposed a diagram including three cycles ensuring rigor in design research. The relevance cycle defines the problem and provides requirements for the test environment. The rigor cycle is input for the next stage to make sure the results are valuable. With the input of these two cycles, the design cycle is a loop of building and evaluating.

To establish preference and (dis)comfort in the “chaise longue” compared with a 32” traditional aircraft seat, 29 participants including 15 males and 14 females aged 20 to 49 (28.03 ±6.33) were asked to sit in both seats. The BMI of the participants ranged from 15.78 to 34.15 (23.86 ±4.17). Table 4.1 presents the average data for each gender group of female and male participants, including age, height, weight, BMI, hip width, popliteal height, and buttock-popliteal depth. Considering the shortest cruising time of flights is around 40 minutes, the duration of each scenario is set to be 40minutes. The participants were asked to sit 40 minutes in the upper and lower row of the “chaise longue”, (see figure 4.2) and in the traditional aircraft seat placed at 32” pitch (see figure 4.3). All three conditions were the reclined conditions. Permission was given by the ethical committee of the TU-Delft. After welcoming the participants, they completed the informed consent and were instructed on where to sit and how to complete the questionnaires. The participants were studied in groups of 3. The order was arranged by the Latin square method. Comfort/discomfort questionnaire and local postural discomfort (LPD) questionnaire [154] had to be completed every 10 minutes in each condition. The comfort/discomfort questionnaire had an 11-point Likert scale (0= no comfort at all; 10= extreme comfort). The discomfort was a body map with 12 regions and in each region a score from 0-10 could be given (0= no discomfort at all; 10= extreme discomfort). During the test, the participants were asked to behave just like in an aircraft and they were allowed to use mobile phones and listen to music. After experiencing each condition, participants were asked to have a break to reset their bodies. Sitting during the break time was not allowed. After experiencing all three conditions they were asked to complete a questionnaire with questions on preference and comparison of the conditions. This included also an open question on whether participant think the “chaise longue” has the potential for application in future aircraft economy seats and an explanation of the answer. These answers were analysed and the number of the same or likewise wordings was counted.

All questions were completed digitally (online) by the participants and the answers were automatically transferred to excel files. The comfort/discomfort scores (every 10 minutes) were normalized using the min-max scaling [155]. Shapiro-Wilk tests were conducted to check the normality of comfort and discomfort rankings under different conditions. Similar to many comfort studies, the comfort and discomfort scores were not normally distributed. With this understanding, the Wilcoxon signed-rank test (p<.05) was used to check differences of comfort and discomfort scores between the three sitting conditions (upper row reclined seat, lower row reclined seat and the traditional economy seat). Besides the overall rankings, the results of the LPD questionnaires were also studied with similar approach. Comparisons between (dis)comfort scores at the beginning and the end were also conducted to check whether there was any significant difference after 40 minutes sitting in different seats, respectively. After the experiment the participants were interviewed and asked for their opinion on the seat.

Table 4.1 Body measurement of the participants.

	Females (n=14)	Males(n=15)
Age(years)	26.43±5.14	29.53±7.11
Height(cm)	161.21±6.55	178.80±5.69
Weight(kg)	57.99±9.99	80.71±12.12
BMI	22.45±4.76	25.18±3.15
Hip width(mm)	371.57±31.06	398.93±27.43
Popliteal height(mm)	447.21±32.48	513.67±22.20
Buttock-popliteal depth(mm)	479.86±36.98	531.53±33.59

[redacted]

Figure 4.5 The traditional seats used in the test. Participants were asked to sit in the 2nd row. The seat pitch was set as 32’’ as well

Results

Figure 4.6 shows that the majority (76% of the participants) prefers the chaise longue seat. Also, for reclined sitting, sleeping and watching IFE the chaise longue has most preferred scores. However, for using the smart phone and for in- and egress the majority prefers the traditional seat. Table 4.2 shows that most participants experience the upper row as spacious and comfortable.

The open questions and interviews gave more understanding for this phenomenon. Most participants (26 out of 29) see potential in the chaise longue (see table 4.3), but they also see the need for improvement. Four mention that much is to be improved, one mentions that the armrest needs to be added, one mentions that the footrest is too high and one that legroom needs improvement. The potential is having more living space creating comfort in a long journey. For the three participants that see no potential in the chaise longue (see table 4.4), two mention that the seat is inconvenient and one mentions that in- and egress is an issue, claustrophobia could be a problem for the people sitting in the lower row and no windows is an issue as well (while in reality windows might be possible).

The comfort and discomfort scores during the seating did not differ significantly among the three conditions (see figure 4.7). This was surprising as there is a clear preference for the “chaise longue”. Figure 4.7 shows the change in perceived comfort and discomfort in 40 minutes duration. Most differences were not significant. There is a trend that comfort is not dropping that much in general and the least drop of comfort happens when participants sitting in the upper row reclined seat. No significant difference was found among comfort ratings over 40 minutes. The upper row reclined seat was rated with the least discomfort from the beginning to the end of the test. It is also the only seat has a slight drop at the end of the experiment. A significant difference in discomfort was found between the normal economy aircraft seat and the upper row reclined seat at 30 minutes (p=0.043). Besides, the figures also suggest large standard deviations in the ratings on both comfort and discomfort in three conditions. Few differences regarding scores of the LPD are found. Compared with the discomfort (0.028±0.08) when sitting in the lower row reclined seat, a higher discomfort (0.166±0.306) on the right shoulder was reported when sitting in the upper row reclined seat at the beginning of the test. Another significant difference was found on the right upper thigh of participants between the economy seat (0.161±0.248) and upper row reclined seat (0.075±0.213).

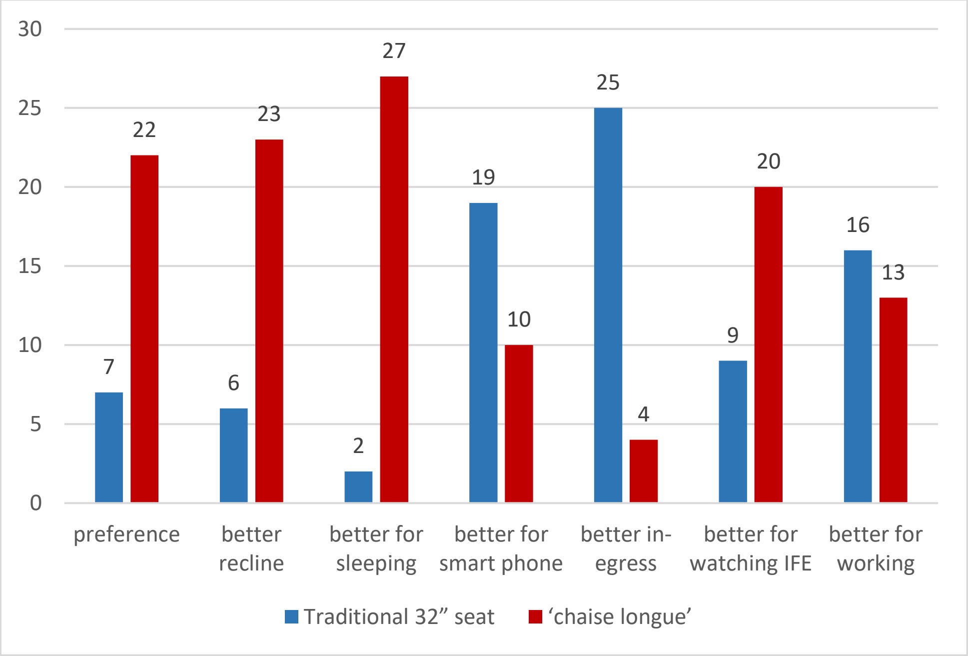

Fig 4.6 Preference of the 29 participants for the seat after experiencing 40 minutes each seat

Table 4.2 Preference of the 29 participants for the seat after experiencing 40 minutes each seat

	traditional	Upper row	Lower row
more spacious	1	20	8
more comfortable	6	14	9

Table 4.3.Points mentioned on the question whether the participant thinks the Chaise Longue has the potential to be the next generation of airline economy seats in the answer yes (26 participants)

Packing efficient/more space	9
comfortable on long journey	6
Much to be improved, but solid base	4
Better posture	1
Extra leg room	1
adaptability	1
Good for sleep	1
For tall people	1
Foot rest too high	2
arm support to be added	1
more ergonomical	1
leg room should be improved	1
only the lower has potential	1

Table 4.4 Points mentioned on the question whether the participant thinks the Chaise Longue has the potential to be the next generation of airline economy seats in the answer no (3 participants)

not convenient	2
high row difficult to access	1
claustrophobia	1
upper row has no window	1

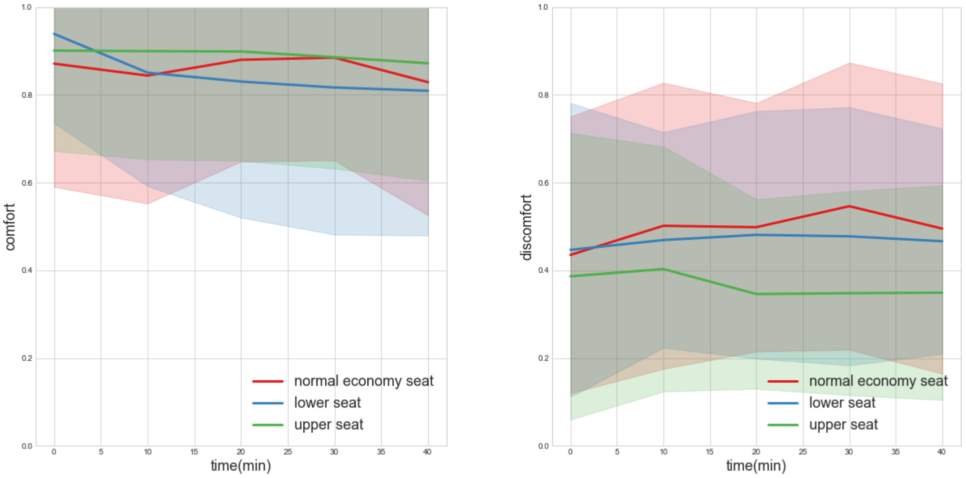

Fig 4.7 Comfort and discomfort ranking in time (40 minutes), with the standard deviation in a lighter color.

Discussion

The chaise longue is preferred by 76% of the participants and 90% see potential in this seat. However, the effect of comfort and discomfort did not affirm this difference between the chaise longue and the traditional seat. There could be different reasons for this. The participants already mentioned points of improvement, like the addition of armrests and improvement of the leg space. It could also be that the cushions were not optimized for the chaise longue as existing cushions were taken. The cushion is among the top five elements of the seat regarding seating comfort [39,214,215]. Another explanation could be that Vink and Hallbeck [10] indicated the comfort/discomfort experience is based on a comparison of expectation and the perceived effects. In this case, the preferences of the users showed the high expectation, which might further enlarge the gaps between the expectation and the perceived effects, e.g. the cushion, the arm rest can be further optimized. The enlarged gap may subsequently result in lower comfort and higher discomfort scores. The answers to the open questions support this explanation.

Lim et al. [216] already showed that the validation of low-fidelity prototyping test results is difficult, because it is unknown whether the results are the effect of the prototype itself or the essence of the design concept. Therefore, the answers to open questions might be more valuable as these show that participants were able to look beyond the existing low-fidelity prototype, which was far from optimized yet.

Using these low- fidelity prototypes, the design science research method was used. The strategy was to have fast design iterations to gain knowledge and improve the product. For each field study, the solution/product does not need to be perfect but the results should provide new insights for a better design [217]. This is also much related to the design strategy of design as research in which improving products in specific areas is seen as a primary research focus [218]. Gaining comprehensive insights of specific topic and improving the design complement each other during the process.

Comfort and discomfort scores did not show significant differences, between the traditional seat and the chaise longue, while the majority sees the potential of the chaise longue. Especially, the extra space and the possibility to sleep on long journeys (27 out of 29 mention this) were appreciated. Additionally, the test makes it clear that some elements need attention in the next versions, like the armrest, footrest, claustrophobic effect in the lower row, in- and egress and the fear of not being able to look out of the window in the upper row.

Usually comfort declines and discomfort grows over time [219]. However, although not significant, the new designed chaise longue showed a different trend regarding comfort. This is especially true for the lower row seat that the longer the participants do sit, the more comfort they feel (see figure 4.7). This might be explained by the fact that participants really had to get used to the new situation, which at first looks claustrophobic and later is experienced as nice.

A clear limitation of the study is that it is really a conceptual model and the context was not an aircraft but a lab. This limits participants’ opinion [216]. Another limitation of the study is that not all possible positions were tested. However, the greatest benefits were expected in the two reclined conditions when compared to the current recline. Perhaps more information was gathered when also the upright positions were tested as well. However, the comparison of all reclined conditions makes it better comparable. Perhaps the 40-minute sitting duration was not sufficient to demonstrate differences, considering that other studies have indicated fluctuations in comfort in 2 hours [118]. Also, it was confirmed that comfort reduces and discomfort increases over time [219].

Additionally, the low fidelity model and context are far away from reality. Some studies state that low fidelity prototypes can keep up with results provided by fully operational products [220,221]. Other studies state that there are differences between a low fidelity and a full functional prototype [222,223]. In our case it is also clear that there are large differences between the studied prototype and operational seats placed in the real context, which might lead to hardly any comfort differences. On the other hand, it was clear enough to the participants that the prototype showed potential. Perhaps with low fidelity prototypes, a very specific comfort questionnaire is not the best to apply and a more open discussion is more fruitful in such an early phase of product design.

The angles in this study were all fixed due to a safety consideration in the lab set up, which may vary in the actual aircraft. In the real scenario, passengers can adjust their seats for a better experience. The combinations of seat pan angle, backrest angle and surface friction coefficient can still be studied to make a better configuration [224]. The dimensions in current design is aiming for the maximum use of space in the Flying V aircraft, but consideration of the visual effects of the space might need attention. Also, if it is to be used in other aircraft models, adjustments should be made according to the corresponding aircraft model's spatial environment to avoid collisions during the flight that may cause injury to passengers. This should be solved in next design iteration by optimizing the dimensions of the seat base on the golden section to harmonizing the space [225].

Conclusion

In general, for research in design, it is important to add open questions and to make the design as close to the realistic version as possible, which is also advised in other studies [219]. Comfort and discomfort questionnaires become more relevant at a later stage of development when the prototype used in the experiment closely resembles the mature product that users interact with in their real lives. However, the “chaise longue” concept has a clear potential for giving more personal space and using the vertical volume in an aircraft cabin. Although the comfort and discomfort scores are mostly not significant, a potential for improvements for a better comfort experience is seen in chaise longue, especially the upper row seats. As a design in an early stage, involving users is helpful to find problems and make space for further improvement. For chaise longue, some practical issues are also obvious such as lacking of support for arms when using smart phones as well as in- and egress the seats. Further improvement focusing on these practical issues need to be done and the tests with close to life experience will come later.

5. Discussion and conclusion

Overview of the thesis

This PhD thesis contributes to knowledge on what should be researched regarding comfort to improve the aircraft interior design for a better comfort experience. The scope of this PhD thesis incorporates three topics: comfort, air travel and design.

The work presented in this PhD thesis involves different elements in the process to how humans experience comfort and discomfort. Measurements were taken to study interaction, human-body effects and perceived effects. The main focus of each study is marked with a star in figure 5.1. Chapter 2 focuses on the factors in the environment of the aircraft cabin. Chapter 3 focused on the objective measurements of the interaction during the main task of passengers in cabin, namely sitting activities. To change this interaction a design of a new seat using the vertical space in economy class was presented in Chapter 4.

The exploration mentioned in this thesis encompasses the process of how people become aware of their comfort situation. Through meticulous measurements and astute observations, the thesis investigates various crucial aspects, including interactions, human-body effects, and perceived effects, all of which play pivotal roles in shaping our comfort experience.

The central focus of this research lies in the interactions between humans and the aircraft cabin environment. By measuring different parameters and studying the interactions occurring at the interface between the human body and the environment, the starting point of the comfort experience, the study examines how the human body receives signals from the environment. Delving into the physiological factors at play, the thesis explores how these signals are transformed within the human body. By capturing and analyzing the subjective feedback of participants, the research gains insight into how people consider their comfort level in the environment. By researching the relationships between these different aspects, a comprehensive picture of the human comfort experience in the aircraft cabin can be drawn.

The exposure time can be a decisive element for factors to make impact on perceived comfort and discomfort. This is already mentioned in the work of Vink et al. [77]. Some factors only influence (dis)comfort in a very short time and then people can adapt to it. Other factors need longer time to develop and make a difference. The climbing phase of aircrafts creates a special comfort experience for passengers and it might be too short to influence (dis)comfort. Sammonds et al. [40] found that it usually takes about 40 minutes for car drivers to feel discomfort and the climbing phase is usually shorter.

Since sitting in the cruise phase of a flight is the main activity in an aircraft, objective measurements are usually taken in this phase to record the interactions during sitting (e.g. [39]). Many studies have been conducted to explore pressure distribution and perceived (dis)comfort [42,43]. Fujimaki and Noro [41] confirmed in their study that pressure distribution could reflect the interaction between human and the seat by showing the changes on the pressure map caused by movements of the person. Besides the pressure distribution on the surface between human body and the seat cushion, sitting (dis)comfort could be reflected by pressure distribution below the seat cushion as well, which was studied in this PhD. This offers the possibilities of recording pressure distribution during long-term experiments and real flights, also because the change of damaging the recording system is lower. However, other ways of measurements linked to (dis)comfort are more difficult to link to comfort. HRV, the physiological parameter used in Chapter 3, correlated to comfort but it was hard to explain how it compares to perceived discomfort of passengers. As a sensitive indicator reflecting central–peripheral neural feedback and CNS (central nervous system)–ANS (autonomic nervous system) integration [135], discomfort may not be reflected very well in a stable calm state in short time.

This PhD also shows that the comfort in the design of the aircraft interior is hard to evaluate using low-fidelity prototypes but testing in an early stage of a design could bring valuable insights and understandings of passenger experience in other aspects broader then comfort, like the vision on how passengers see its use in the future.

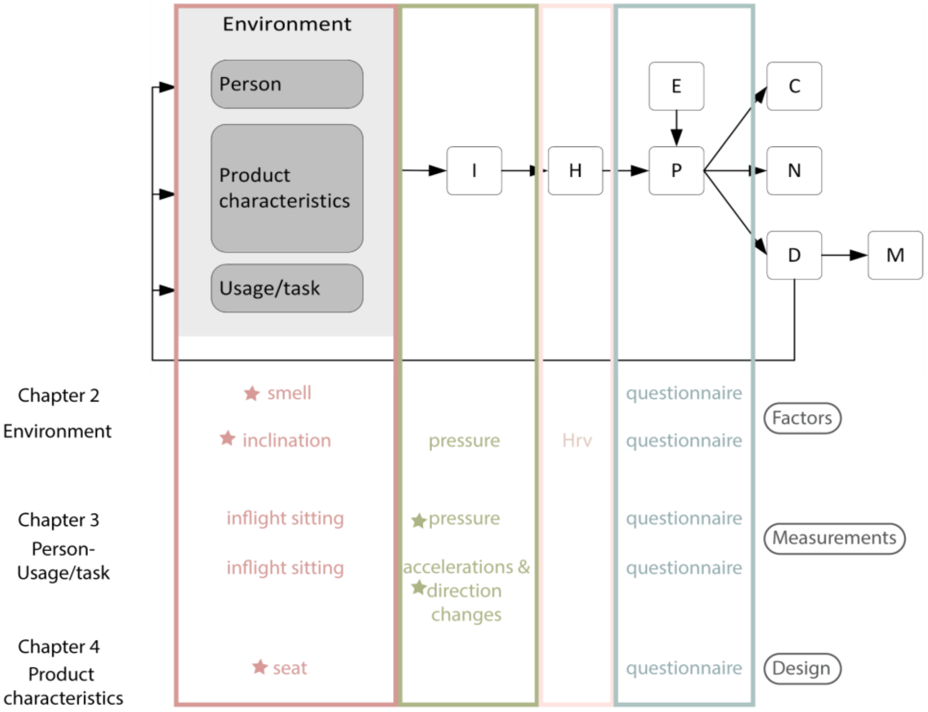

Figure 5.1 Summary elements studies in the thesis related to a comfort model

Answers to research questions

Chapter 2-RQ 1.1: What are the effects of different scents on perceived (dis)comfort of aircraft passengers?

Scents could make impact on perceived comfort and discomfort of passengers. There are large differences between individuals. Different scents (and intensity) influence perceived comfort and discomfort differently. The scents of mandarin performed better than lavender and cedar. The perceived comfort with the mandarin scent was significantly higher at group level than the control group on the same day. It could be explained as it is linked to food and positive effects on comfort have been found when food is served in cabin according to Bouwens et al. [226]. However, the effects of scents change over time and no significant differences were found between different scents and control groups after 60 minutes. Interesting is that with noise a similar effect has been found in the EU project ComfDemo [227]. The discomfort rating caused by noise decreased from ascent to descent in time. None of the scents could change the trend of discomfort increase over time [36]. The results show that scent might influence males more than females although females actually have more neuronal and non-neuronal cells in their olfactory bulb than male, which might indicate a higher sensitivity on smell [84]. This should be further researched as in our study the sample size of different genders was limited in this study. Furthermore, this study solely focused on the introduced scents within the aircraft cabin, and the range of scents investigated was quite limited. While not addressed in this thesis, it is important to note that bioeffluents and VOCs in enclosed spaces also have a significant impact on passengers' well-being [228,229], warranting further attention.

In general, large variations in outcomes were observed in this study. Some of the variations are determined by individual differences in gene [85] indicating great challenges in improving comfort experience by using any unitary scents in cabin. However, it brings the design opportunities of personalized “mass-produced” items in aircraft cabin which might increase the attractivity of the flight [87].

Chapter 2-RQ 1.2: What are the effects of different inclination angles on comfort/discomfort experience of passengers during the climbing phases of a flight?

In this study, three angles were tested in a Boeing 737 cabin: 3 degrees was set up for cruise simulation [119], 14 degrees and 18 degrees were used to simulate climbing angles since the smallest and largest climbing angles of most Boeing 737 and777 series are 14 degrees and 18 degrees respectively [95]. Participants experienced each configuration for 20 minutes as the climbing phase is usually this length. In all the configurations, discomfort increased and comfort decreased over time which is in accordance with previous studies (e.g. [40]). Climbing with 14 degrees is recommended based on the results that a similar performance was found for the cruising stage angle regarding perceived comfort. In the 14-degree setting, the smallest COP moving speed, which indicates the captured movements on both the backrest and the seat pan, was observed among the three settings. The less/smaller movements could be the result of less discomfort [41].

Chapter 3-RQ 2.1: Which pressure map measures (including the division of pressure of the contact area) are more suitable for evaluating the comfort/discomfort experience of passengers and can the relationships between comfort/discomfort and the pressure map be captured under the cushion?

In this study, the relationships between the perceived comfort/discomfort and pressure in different areas in the contact area are studied. Six existing division methods and one newly proposed division method of the pressure map were explored. Data were collected both at the top of and under the cushion. The results of the study showed the advantage of dividing the pressure map with the new method, which is a combination of the work from Kilincsoy [43] and Lantoine et al. [42]. The location of the crotch point is used to divide buttock and thigh, as well as the left and right side, another horizontal line is used to split thigh area equally into proximal and distal posterior thigh due to the different sensitivities of these two parts [43,158].

Comparing the pressure map at the top to under the cushion, showed that the regions with high correlation values related to (dis)comfort differ. The measures of bottom pressure map had larger correlation values to comfort than discomfort, which indicates the potential of using pressure maps at the bottom of a cushion for long-term comfort studies. As there is no direct contact between the pressure mat and human body, the material of the pressure mat will not influence the comfort experience of users and it is less sensitive to damage.

Moderate correlations were found between different pressure parameters and (dis)comfort, confirming the importance of studying both comfort and discomfort of aircraft seats. The most prominent parameters found in this study are contact area, force and mean pressure, which is in accordance with previous literatures [128,150]. However, the fluctuating performance of individual measures regarding different stiffnesses of the cushions make it necessary to synthesize multiple measures in predicting comfort/discomfort in future research.

Chapter 3-RQ 2.2: Is it possible to recognize inflight sitting postures with loose-fit wearables and how do the loose-fit wearables perform regarding comfort and discomfort compared to the tight-fit wearable?

It was confirmed that using loose-fit wearables are sufficient in inflight sitting posture recognition. A loose-fit wearable and a tight-fit wearable with same sensors and sensor distribution were used to recognize 7 common inflight postures. The accuracy of recognition are 74.8% and 65.8% respectively. Both wearables showed a low accuracy in detecting a slumped position due to the limited space and variation in body sizes. Also, problems occur when recognizing whether people are leaning to one side or rotating their body. Optimization of sensor distribution may be needed for improvement. Overall comfort and discomfort were also reported in this study and the results showed that the loose-fit wearable performed significantly better regarding both comfort and discomfort due to less limitation in movement [230]. Since people with different body shapes may have differences in skin sensitivity [16], the loose-fit wearable also showed a better inclusiveness as the space between the cloths and the human body gives more movement space. The findings of this study suggest that ergonomic considerations and the need of technical accuracy are not mutually exclusive in wearable design. Furthermore, the study underscores the potential for creating and utilizing wearables with better comfort experience in a variety of contexts beyond their current applications.

Chapter 4-RQ 3.1: Is the seat design ‘chaise longue’ using the vertical space in a new way preferred above a traditional aircraft seat positioned at 32” pitch and could the comfort experience of passengers be improved with the new design?

A within subject experiment involving 29 participants was conducted to establish preference and (dis)comfort in the “chaise longue” seat compared with a 32” traditional aircraft seat. After experiencing a traditional aircraft seat, participants experienced the lower “chaise longue” seat and the upper “chaise longue” seat for 40 minutes per seat. The participants scored (dis)comfort and gave their opinions. The majority (76% of the participants) prefers the chaise longue seat because of the advantage of reclined sitting, sleeping and watching IFE. Most people saw the potential and mention that the “chaise longue” provides a more spacious and comfortable experience. This is especially true for the upper row. The upper row of the “chaise longue” was also rated with the least discomfort from the beginning to the end of the test. However, the comfort and discomfort scores during the seating did not differ significantly among the three conditions.

Probably, it is hard to establish significant differences between (dis)comfort scores due to the low-fidelity prototype [216] but the suggestions gathered for the future improvement of the design are valuable, for instance, the fact that participants mentioned the addition of armrests and improvement of the leg space. The cushion should also be adapted as an existing cushion was used and it should fit to the shape of the new seats, as it is among the top five elements of the seat regarding seating comfort [22,39,214].

Future work

Many studies have found the importance of time and how (dis)comfort develops as time changes. Sammonds et al. [40] presented the pattern of discomfort growing over two hours during driving under controlled conditions in the lab. Smulders et al. [125] showed how comfort decreases in 90 minutes of sitting in a business-class aircraft seat based on a 3D human model. However, perceived (dis)comfort is a result of multiple factors working together. How the synthesized effect of different factors on comfort changes over time still needs to be explored. Bazley et al. [73,231] compared the difference in discomfort during weekdays of people with different occupations and indicated that time influences (dis)comfort differently in different working environments and with different working types. Studying the effects of time can be crucial to support occupational health and establish a reasonable working rhythm.

In comfort studies, objective measurements should be used together with questionnaires to understand the interaction that is happening between humans and the environment, thus explaining the perceived (dis)comfort. So far, environmental factors (including product features), interactions, and human body effects could all be measured with objective measurements [24]. This offers an opportunity to combine multiple objective measurements in different aspects mentioned in the comfort model developed by Vink and Hallbeck [10] to gain insight into what happens in each stage when stimuli occur and how the signals input from the environment finally make an impact on perceived (dis)comfort.

Since (dis)comfort is about human feelings in reaction to the environment, product designs and interior designs for a better comfort experience should be evaluated in the context of use. However, it is not always possible to build the exact environment of use, and low-fidelity prototyping may cause inaccuracies in the evaluation [216]. Using mixed reality can be a solution for design implications of comfort theories. Kent et al. [232] conducted a systematic review, including 108 papers on the use of mixed reality in design prototyping, and the trend is clear that mixed reality is used more and more in prototyping for combining the tangibility of physical products and the replicability of visual effects. This can be very useful for comfort design in special contexts, such as aircraft. The low-fidelity prototype can be used together with virtual reality technology to provide an immersive experience for users, and the design can be evaluated in an early stage for improvement.

Based on the experience obtained in this PhD thesis, some practical suggestions for future research are formulated. Firstly, the measurements concerning comfort in the aircraft interior should be carefully planned. It is advised to consider which data should be gathered. Data from different perspectives can be collected with multiple measurements, like the one used in this PhD: pressure distribution, postures of body parts, observation, movement of body parts, temperature, humidity, heart rate variability, dimensions of the environment, interviews and questionnaires. These data are helpful for researchers to explore the link between (dis)comfort and the background of this (dis)comfort, as well as to understand the atmosphere. However, the measurements could also disrupt the experience and create noise in the results. For instance, the observation or placing of ECG equipment can influence the behavior of participants. The amount and type of measurements should be decided carefully to balance the richness of the insight and the accuracy of the results. Secondly, studying the aircraft interior is very useful in an early stage before building the aircraft. However, the aircraft cabin is an environment that is very difficult to simulate due to the fact that for instance movement (including vibration), noise and air pressure are hard to simulate. A chamber built with a real aircraft cabin can be very helpful in obtaining accurate data by providing an accurate environment, creating a close to reality experience. A lesson learned from the experiments in this PhD is that conducting experiments with the involvement of real passengers in the early stages was always helpful in understanding the environment and people's reactions. Perhaps the knowledge on anatomy, physiology, and neurology could be deepened as it might be interesting to understand what happens inside the human body and how people become aware of their (dis)comfort levels. However, the question is to what extent this knowledge should go as at going to a microscopic level might be interesting but very complex. For now, this PhD research generated new knowledge on the relationship between (dis)comfort and scent, angle of the airplane, pressure map division, recording pressure at the top and bottom of the cushion, using the vertical cabin space and wearing a jacket.

6. References

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List of publications

Publications in this thesis:

Chapter 2:

1. Yao X, Song Y, Vink P. Effect of scent on comfort of aircraft passengers. Work. 2021;68: S273–S280. doi:10.3233/WOR-208025

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Chapter 4:

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