THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF MECHANICAL ENGINEERING

ACCEPTABILITY, SUFFICIENCY, AND COMFORT IN MODERN AIRLINE SEATING BASED ON BIDELTOID BREADTH

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SPRING 2024

A thesis
submitted in partial fulfillment
of the requirements
for a baccalaureate degree
in Mechanical Engineering
with honors in Mechanical Engineering

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Abstract

The objective of this senior honors thesis is to develop different relationships on comfort, acceptability, and sufficiency with respect to shoulder width in modern airplane seating. This thesis focuses particularly on bideltoid breadth, or shoulder width, as a key metric in determining acceptability and sufficiency of width and space. When it comes to human anthropometry, nearly every single person has a bideltoid breadth that exceeds their seated hip breadth. As a result of a secular trend in increasing BMI in the adult population, as well as decreased seat size in airlines, a passenger's perception of personal space is altered. This thesis seeks to pose different experimental boundary conditions meant to simulate real-life airplane conditions to determine how passenger interactions affect comfort, acceptability, and sufficiency.

This thesis outlines the relevance of this study given the increase in BMI and decrease in seat size, background of human anthropometry and designing for human variability to promote accommodation, and the experimental setup and results found from the data analysis. The experiment presented featured numerous human trials and a robust set of data procured from individuals varying in stature and BMI, aiming to gather enough data to be representative of a real civilian population. From the data gathered, the conclusion was such that a seat width set equal to someone's bideltoid breadth was rated at a higher comfort level than any other condition presented, indicating the need for accommodating passengers based on bideltoid breadth rather than their seated hip breadth.

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Acknowledgements

This thesis would not have been possible without a number of people in my corner supporting me through the past four years of my undergraduate education at Penn State.

To Mom, Dad, and Cal (and Leo) – for always supporting me throughout college. I have a thesis now! You'll never truly know how much you all mean to me. From Dad driving me to and from State College 300 times a year to Mom making sure I have everything I need (including soup for my sad esophagus) and her behind the scenes work that's never fully appreciated to Cal for just being the best little brother in the entire world, you are my rocks and my everything. Life would be so boring without you. Thank you for being endlessly supportive throughout my four years at Penn State – onto the next adventure in grad school!

To my thesis supervisor, Dr. Matt Parkinson – for being a mentor and someone who I have looked up to since the very first day of EDSGN 100H my freshman year. Thank you for your guidance, sense of humor, and for inspiring me to be a better engineer. Thank you for teaching me all about designing for human variability, thinking outside the box (canoe project anyone?), and how to correctly drive on the highway. I hope to be like you when I grow up.

To my honors advisor, Dr. O'Connor – for being one of the coolest people I know. I could not be more grateful to you and all your support over the last 4 years. After way too many emails sent in a panicked state and even more sent with good news, I'm so happy to have had an advisor and mentor like you.

To my other honors advisor, Dr. Byron – for making sure all my ducks were in a row, keeping my thesis on track and giving great feedback, and for being a great advice giver. Thank you for everything you've done for me and all your other advisees over the past year.

To my friends who always allowed me to rant to them about this thesis, asked me if I needed anything, and who distracted me when I needed a break – I am so grateful to have you all in my life.

It took 30 Big Booty Mixes, 19 double shot espressos, hundreds of Stack Overflow and Stack Exchange searches, a couple conversations with Tough Kelly, and more pep talks in the Reber E-Knowledge Commons than I can count, but this thesis is complete.

Chapter 1

Introduction

1.1 Why We Design For Human Variability

In recent years, the adult obesity rate in the United States has increased to 41.7% [2]. With both an increase in body mass index (a measure of weight-for-stature) and body measurements, current airplane seat dimensions are no longer acceptable to a large number of the population. When it comes to the secular trend of increased BMI and an increase in body size, the importance of designing around variable human anthropometry is a crucial part of designing for human variability.

It was with the development of spacecraft that the interest in designing for human variability amplified and became a central focus in centering a design around human bodies [3]. Although humans in spacecraft spurred an interest in design for human variability in human-occupied spaces, the practice can be applied to the design of modern day commercial aircraft. According to the 2017 Federal Aviation Administration forecast, the rate of commercial carrier plane usage in the United

States will increase 1.9% yearly until 2037 [4]. Additionally, the domestic capacity of planes in the United States has increased 5.3%. Furthermore, the load factor (the percentage of filled seats in an airplane [1]) of domestic aircraft is expected to increase from 84.1% to 86.3%. With an increase in the load factor, the density of passengers on an airplane increases, and so do the levels of disaccommodation for all passengers as a result of increasing body size. With a decrease in seat widths (width between armrests) from the early 2000's, airlines' desire to continually increase load factor, and trends of increasing body size, more people experience disaccommodation in aircraft than ever [1]. Rather than being an afterthought, human bodies should be the metric for designing in human occupied spaces.

1.1.1 Comfort, Discomfort, and the Factors Which Influence Them

In the design of the human-occupied spaces of airplanes, passenger comfort is an important factor. Comfort is not simply a lack of discomfort, but rather is a composite of numerous factors that intersect to determine comfort [5]. In a 1996 study using 700 office workers, questionnaires were distributed to determine user feelings on comfort; findings were that feelings of comfort were associated with users having a sense of well-being. Additionally, personal space, autonomy, and privacy were additional factors influencing comfort [1]. Discomfort is described by more "pain" words like "cramped" or "stiff," whereas comfort is associated with both someone's feelings in a space and the amount of personal space they have.

When it comes to discomfort, the invasion of personal space by another human—rather than an object in a space—leads to a lack of comfort in a space [6]. Relationships between passengers also play a role in personal comfort; while people who may be friends, related, or in a relationship may be comfortable next to one another, a passenger experiences discomfort when seated next to a stranger. Personal space in human-occupied spaces has been examined in places other than planes—on trains during rush hour travel, the density of passengers on the train is higher than usual, increasing the number of people in the seats. During rush hour, this means that people who are sitting in the middle seat are more likely to sit next to a stranger [7]. Additionally, the denser the travel scenario was, the higher measured stress of the passenger was after the experience. It was shown that passengers in this scenario would rather stand by themselves than sit in the middle seat and avoid the physical proximity to a stranger that is guaranteed in a densely packed train [6]. Passengers in human occupied spaces identify physical proximity as being the most frustrating invasion of someone's space [8]. With the increasing body size of passengers globally, passenger bodies are more likely to touch one another, leading to a more uncomfortable environment. Personal space does not just include the physical aspect of space but encompasses an overall encroachment on the senses in an environment [6]. Other facets affecting personal space include the age or gender of an adjacent passenger, the personality or nature of conversation between passengers, the cultural differences, and the overall room density. Air travel inherently leads to the invasion of personal space since passengers are seated next to strangers in a confined space for an extended exposure period. Discomfort, however, lies not only with passenger interaction, but is largely related to the physical boundary of a seat.

Seat pitch influences the perception of space someone has in an airplane [9]. Pitch can be defined as the distance between the same point in adjacent rows (Figure 1.1). An additional factor influencing personal space in airplane seating scenarios is *legroom*. The required amount of legroom has a direct relationship to someone's height. Although seat pitch is a factor which impacts personal space in airplanes, the study which will be presented in this thesis focuses on seat pitch and the human anthropometry which impacts it, including BMI, seated hip breadth, and bideltoid breadth.

1.2 Increasing Accommodation

When a design fails to consider certain individuals, it leads to the designing out of certain populations. However, certain solutions exist to increase the accommodation of users. Comfort and fit meet at the crossroads of accommodation, and each are not determined by one thing, but rather, are multivariate in nature. Multivariate design (the simultaneous consideration of multiple design

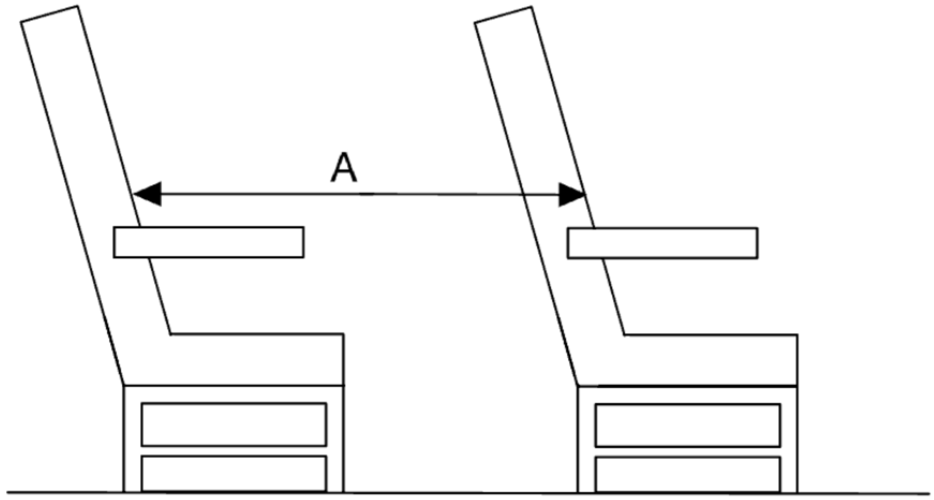

Figure 1.1: Visual description of seat pitch (A)

factors) takes different anthropometric relationships into account when it comes to design—for example, measures of length are correlated with one another, whereas measurements of breadth are considerably less correlated with length. Consider the relationship between arm length and stature; these two measurements are related to one another through certain proportionality constants. However, measures of length (like stature) and measures of breadth (such as hip breadth) have a much looser correlation. BMI has a much stronger relationship to measures of breadth, thus, accommodation is not solely proportional to a single measurement such as stature, but occurs through taking multiple different measures into account. Every person's body has unique anthropometry, and not all measurements correlate linearly or at all with one another. Using a multivariate design approach is essential to have more well-rounded accommodation. To get a higher level of accommodation, using multivariate design guarantees more considerate design and a true approach of designing for human variability.

Besides multivariate design as a method to increase accommodation, adjustability can be considered. User needs and preferences are better accommodated when they have the option to adjust a design; for example, desk chairs with adjustable seat height or armrest height to accommodate a range of preferences. Alternately, different sizes being implemented in a design may be a more cost-effective way for a manufacturer to match user preference.

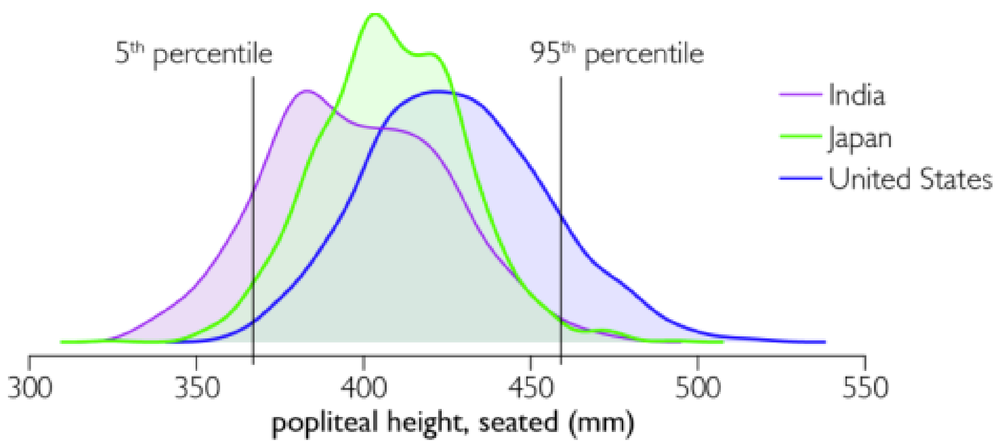

Figure 1.2: Probability density of seated hip breadth in adult men and women - reprinted with permission [1]

In addition to multivariate design and adjustability, designers can use a supplementary method called the "1st and 99th approach" for accommodation [10]. Previously, the 5th and 95th method has been used, which uses the 5th percentile and the 95th percentile values for a certain measurement to achieve accommodation. Although this method should accommodate 90% of individuals, through a univariate approach, it will only accommodate 83% of the population due to unique and unrelated anthropometry (for example, designing a chair based on the 90th percentile buttock popliteal height does not accommodate the 90th percentile of seated hip breadth). This univariate approach is particularly problematic when a product is designed around a certain group; for example, designing around the 90th percentile man, who has a considerably higher stature than most women, will lead to high levels of disaccommodation in women. Since not all measures are not perfectly correlated, the percentage of individuals that are disaccommodated on one measure are not exactly the same as the percentage disaccommodated on another, leading to lower levels than necessary for accommodation. Shown in Figure 1.2 is a visual depiction of the amount of the population disaccommodated when the 5th and 95th percentile approach is used.

Using the 1st and 99th percentile approach in multivariate design leads to an overall accommodation of around 95 percent, which is the key number for true design for human variability across populations, over a 12 percentage point increase in accommodation for global populations. Although minimum accommodation is met with the 5th and 95th approach, the ideal accommodation can be met through the 1st and 99th approach [1]. Since global populations are diverse, compounding the data and using both the 1st and 99th and multivariate approaches allows designers to achieve accommodation of significantly more of a population.

Between multivariate design, adjustability, and a broader range of percentiles used in design, there are numerous ways to create considerate, human-centric design in human occupied spaces and products that designers should keep in mind.

1.3 Relevance of the Problem

With an increase in adult obesity rates [2], an increase in load factor, and a decrease in seat widths in airplanes [1], designing for human variability must be taken into consideration if ideal accommodation can occur in airplanes. Designing for only one part of the population who fits in the current smaller airplane seats fails to account for the upper and lower percentiles of BMI and other measurements, leaving out much the population. Shrinking airplane seats with an increase in body size is a failure to accommodate, but more relevant experiments on space and acceptability in airplanes can be conducted in order to provide better design data for use in airplanes.

1.3.1 Addressing the Problem

Virtual Fitting Trials, otherwise known as VFT, provide a way for designers to create a 3D model of a human with varying body types to be able to visually perceive how someone would be accommodated in a design [11]. One such tool is a program called SAMMIE, which is an acronym for System for Aiding Man-Machine Interaction Evaluation. While SAMMIE and other VFT softwares are valuable tools to provide insight for a design, the most effective way of determining accommodation is through using real human participants and a physical prototype of a design to gather real-world data.

Throughout the experiment completed in this work, human participants will partake in a series of trials with varying boundary condition setups and seat widths. Participants will be matched into “bins” to acquire important feedback from individuals with varying body shape and size. During the trials, participants will give feedback on the acceptability and sufficiency of the seat width and the amount of space they have, as well as their overall comfort, allowing for ergonomic data to be collected and used in the future design for airplane seats that truly accommodate people.

The goal of this thesis is to discover the relationship between human anthropometry and acceptable seat width on airplanes. However, this thesis will focus on the relationship between comfort, seat width, and a person’s shoulder width (bideltoid breadth). The objective is to go through the human trials as described as above to receive human feedback to validate the relationship between their individual anthropometry and varied, personalized seat widths and boundary conditions. The intersection of acceptability and comfort will be examined, establishing a novel relationship between the two. Eventually, these data will be anonymously used in ergonomics publications to provide better, more accommodating recommendations for airline designers.

Chapter 2

Background

The discussion in Chapter 1 regarding the importance of changing body dimensions, comfort, accommodation, and the relevance of the problem highlight why *design for human variability* as a field is important. In this chapter, the focus shifts to the background of design for human variability, including sex and race differences, the importance of designing for human variability in human occupied spaces, and the design of airplanes specifically due to a range of factors, including a population increasing in physical size, decreasing seat size over the years, and an increasing load factor. This chapter highlights the relevance of not only designing for human variability, but will emphasize the purpose of both the study, experiment, and analysis presented in this thesis regarding shoulder width, comfort, and acceptability.

2.1 Differences Between Sexes and Races

A population experiences variation within the same gender; however, the differences between genders, as well as between races, must be considered for an accommodating design. To identify the variability within US military personnel, the ANSUR survey was conducted in 1988 [12]. The resulting data consist of 164 total measurements (comprised of 116 body measurements and 48 head and face measurements) from over 9,000 US soldiers across 11 different bases. Out of the 164 total measurements in this survey, 161 were significantly varied because of gender and race. The measurements that were not associated with race were *axillary arm circumference* and *seated abdominal extension depth*. The only measurement not associated with gender was the *crotch length* measurement. Additionally, a supplementary large-scale survey of U.S. Army Personnel occurred in 1996 as a method of validating the initial 1988 survey results [13]. From this follow-up survey of 6068 individuals, the measurement distribution of both male and female military personnel was still valid a number of years later. Although the most current version of the ANSUR survey is from 2012, it is still the anthropometry of Army personnel and is not representative of the human variability that occurs in a civilian population. The National Health and Nutrition Examination Survey, known as NHANES, provides a database on civilian data, including gender, race, and certain anthropometric measurements [14]. Through the consideration of both ANSUR and NHANES data, a robust set of relevant human anthropometry is available to ensure considerate designing. With the culmination of results from 1988 and 2012 ANSUR military personnel surveys and years of NHANES civilian data, both racial and gender differences can be seen in these data reflecting the need for designing for human variability.

2.1.1 Sex Differences

Men and women, from an anthropometric perspective, have significant differences between them that should be considered during design. Women have a higher average seated and standing hip breadth than men in absolute terms, but also have proportionally wider hips overall [15]. The most prevalent anthropometric gender differences lie within the sex characteristics and the areas of muscle development: the hips, the breasts, and the shoulders (with women exhibiting larger hips and breasts and men having larger shoulders and arms overall) [16]. Figure 2.1 displays the distribution of seated hip widths among adult men and women in a VFT, or Virtual Fit Trial, where

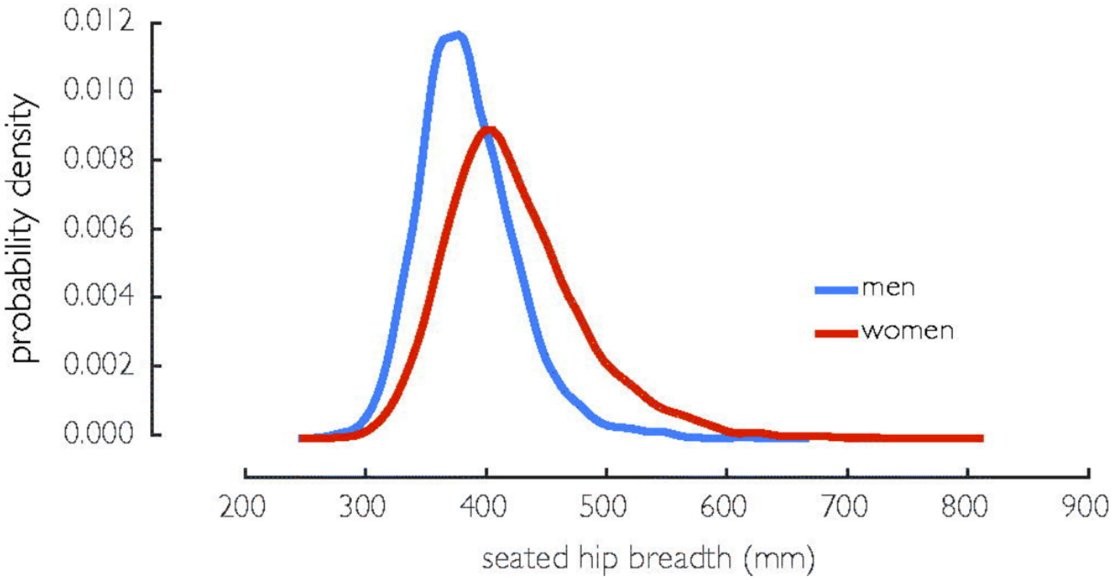

Figure 2.1: Probability density of seated hip breadth in adult men and women - reprinted with permission [1]

3D models of humans are used.

Women not only have different anthropometry than men, but there is also a significant data bias toward men in medical care, technology, and notably, car seats [17]. Since women are shorter on average than men, they're more likely to be sitting farther forward in their seats, thus considering them "out-of-position" drivers and leading to more serious injuries and a higher chance of death in car crashes. The lack of consideration for women in human-occupied spaces makes them 17% more likely to die in a car crash than men. In the United States, a female crash-test dummy was not implemented until 2011, which is likely one reason why women are more likely to experience serious or moderate injury in a car crash. In the European Union, a female crash test dummy was recently implemented into their crash test procedures; however, this female dummy was tested as a passenger rather than a driver and is simply a scaled-down version of a male crash test dummy [17]. Women are not simply small men, but rather have their own distinct anthropometry that must be considered in designing for accommodation not only for their comfort, but their safety.

When it comes to disproportionate disaccommodation between sexes, anthropometric differences are key, especially in human-occupied spaces like airplanes. Anthropometry for men is

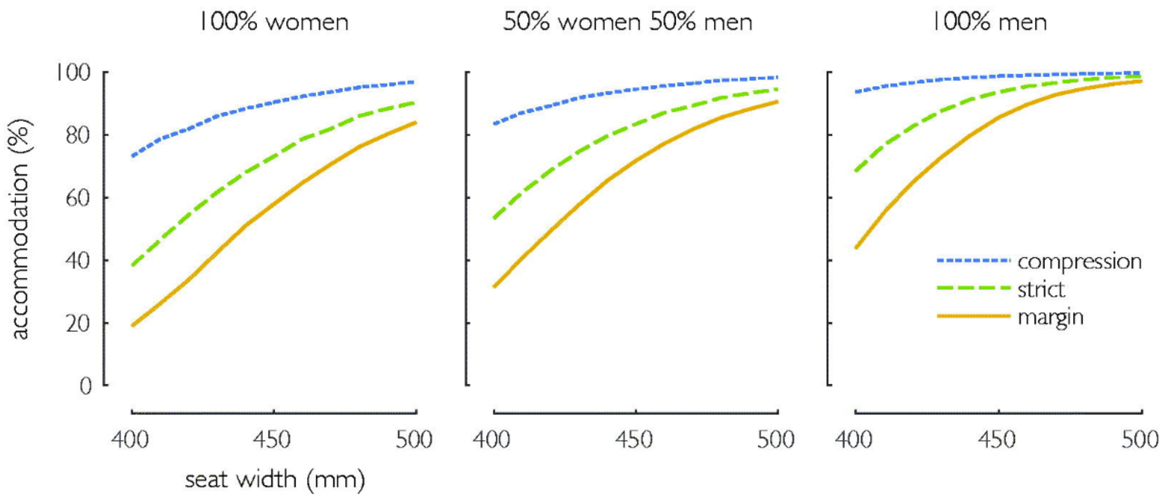

Figure 2.2: Airplane accommodation in seat width based on sex percentages - reprinted with permission [1]

significantly different than for women, which is why when men are used as a sole design metric, whether it is their measurements for a seat or dimensions for a crash test dummy, accommodation for men is far better than for women [18].

When there are more men on an airplane, the overall accommodation is better simply because of the lack of women [1]. Women have a higher average measured hip breadth, and as a result, are not nearly as accommodated as men are in airline seating. As a result of the anthropometric differences between genders and deliberate design based on male anthropometry, women and men must be considered different groups when it comes to accommodation. Shown in Figure 2.2 is a graph of accommodation versus the number of passengers who are men, plotted with a constant seat width and a load factor of 1 (a fully occupied plane).

A plane entirely filled with women will exhibit significant disaccommodation because of their vastly different anthropometry; disaccommodated groups must be focused on if design issues based on accommodation are to be fixed. Women are not just small men, and their unique anthropometry must be taken into consideration when it comes for designing for human variability.

2.1.2 Racial Differences

Just like women are not a scaled-up or scaled-down version of men, different global populations are not scaled-up or scaled-down versions of US men or women. They have their own distinct proportions [19]. With the 1988 ANSUR survey revealing significant variation between races, an important baseline document was created for designing for human variability [10]. Given such a vast range of diversity in anthropometric measurements between different demographics, accommodating more for one group can disproportionately disaccommodate another. Between women and men, the Netherlands has the tallest average height between both sexes [20]. Examining the average height of males in the Netherlands at 1.84 m (72.4 in) versus the average height for males in Timor-Leste at 1.59 m (62.6 in), a difference of 0.25 m, or 9.8 inches, can be seen. For women, the average height is 1.70 m (66.9 in) in the Netherlands, whereas they have an average height of 1.51 m (59.8 in) in Guatemala (with the next lowest from Timor-Leste at 1.52 m), with a difference of 0.2 m (7.1 in). With a several inch difference between the tallest and the shortest populations in both the men and women of the populations, it becomes obvious that accommodating entirely for one race creates significant disaccommodation for another. Overall, individuals with a lower body weight and a shorter stature are more likely to be found in equatorial regions, whereas a higher body weight and a taller stature are more likely to belong to individuals from higher latitudes [21]. More specific differences between races can be found in the 1988 ANSUR surveys based on the tests conducted [12, 13]. Whites surveyed had far larger trunk lengths and trunk circumferences, Hispanics and Asians are greatly prevalent in the lower ranges of size-related dimensions (most notably in stature, span, and weight).

Not only are there different body segment proportions between populations, but the distribution of anthropometry within populations is just as diverse. Every racial group has different proportions and anthropometric distributions; global user populations vary greatly not only within their own population, but also between other global user populations. In order to increase accommodation, certain deliberate steps can be made for the most considerate design possible.

2.2 Changing Factors in Airlines

The adult obesity rate has grown significantly while airplanes are continuously decreasing both the seat pitch and seat width to increase the number of seats and thus, the load factor (the density of passengers) of airplanes. With only a certain amount of space in an airplane to fit seats, an increase in body size, and the desire to fit more people onto an airplane, this quickly becomes an issue of not only user preference and personal comfort, but of accommodation of passengers in human-occupied spaces.

2.2.1 Trends in Seat Sizing and Load Factor

As a result of their desire to increase the amount of passengers that can fit in an airplane and increase profit, airlines have been decreasing both seat width and pitch in recent years [22]. The U.S. Department of Transportation only implements standards regarding emergency evacuation and nothing in terms of passenger comfort; although the importance of safety cannot be ignored, cramming more people into an airplane seems to be more unsafe. The lack of regard for secular trends in increasing body size as an airline focus rather than on profit makes little sense when it comes to accommodated passengers. Regarding seat pitch, the distance has decreased from 35 inches to 31 inches since 2011, occasionally even more in lower-cost airlines [22].

A lack of standardized measurements when it comes to seat pitch is uncomfortable enough, but a decrease in the seat width decreases passenger personal space and thus, comfort, during a flight. A recent study from the Federal Airline Administration aimed to run evacuation tests to analyze changing seat dimensions from a sole safety perspective; using 775 participants from Oklahoma (a population with a larger than average body size), the FAA stated that even the smallest seat width of 28 inches was sufficient for a safe evacuation [4]. However, the FAA states:“The study results do not consider passenger comfort (or the lack thereof), which impacts a passenger’s sense of well-being during a flight.” The blatant failure of airline focus on passenger comfort may additionally impact their safety; as one passenger advocate states: “Physics tells you the more people you pack into a plane the longer it will take to evacuate," indicating that profit-centered airlines affect both accommodation and safety of passengers [22]. Although the seats may be considered "safe" from an evacuation standpoint, the goal of airline designers should reach beyond packing the airplane with as many passengers as possible, but rather show consideration for passenger accommodation, even at the loss of some profit. A reconsideration from federal entities may be valuable to establish a baseline that considers more travelers than are currently accommodated.

2.3 Seat Sizing and Anthropometry

Up to this point in time, there have been numerous datasets on human anthropometry gathered. In this thesis, the datasets that will be used include the expansive ANSUR II dataset of military personnel in the 1996 in addition to the most recent 2015 - 2018 NHANES data (National Health and Nutrition Examination Survey) for relevant U.S. civilian data [14, 13]. A rich dataset is especially present in the ANSUR II data, where hundreds of anthropometric measurements were taken in order to provide better design recommendations for military equipment and occupied spaces. However, for the purpose of airplane seating for civilians, the following anthropometric measurements are of importance:

- Stature: the vertical distance from a standing surface to the top of the head
- Body Mass Index (BMI): a person's stature squared in meters squared
- Sitting height: the distance from the surface to the top of someone's head while sitting upright with their knees at a 90 degree angle
- Seated hip breadth: the horizontal distance between the outside of the hips while a person is sitting with their knees together and at a 90 degree angle
- Bideltoid breadth: the maximum distance between a person's upper arms with elbows at a 90 degree angle

- Buttock-knee length: the distance from someone's buttock to their knee while sitting with their knees at a 90 degree angle

Additionally, the term "seat width" refers to the space between armrests, not the physical seat pan width. As mentioned, measures of length and width are loosely correlated to one another, however, the relationship can be analyzed through finding the R^2 (coefficient of determination) value. Using R Studio, a programming language designed for statistical analysis, and the ANSUR II data for female military personnel, the following R^2 values were determined:

Seated hip breadth vs. Stature: $R^2 = 0.1359$

Seated hip breadth vs. BMI: $R^2 = 0.5911$

Based on the R^2 values above, the relationship between seated hip breadth and stature is the least related; a more accurate relationship is confirmed between seated hip breadth and BMI. The importance of seat width in not only airplanes, but in all human-occupied spaces, is evident through the relationship between BMI and seated hip breadth; where stature is relatively constant in the past years and BMI has soared, hip breadth is greatly affected by the secular trend of increasing BMI.

Airlines gradually decreasing the seat width in their airplanes certainly affects seated hip breadth acceptability, however, the impact extends beyond the seat pan into the rest of the space. Although someone with a larger seated hip breadth would be affected by a smaller seat width, as well as the people next to them, the smaller seat widths impact the personal space of adjacent passengers if their shoulders experience unwanted contact. Using the ANSUR II dataset, 97.3% of female participants and 100% of male participants had a larger bideltoid breadth than their seated hip breadth. Shown in Figure 2.3 and Figure 2.4, the probability density for each gender's bideltoid breadth is farther right than the curve for their seated hip breadth, indicating a larger overall measurement. From the figures, it becomes clear why the decreasing seat size in airplanes impacts comfort; if passengers seated next to one another have shoulders that are touching, their personal space is impacted, leading to disaccommodation and an uncomfortable scenario.

In recent years, there has been not only a decreasing seat width measurement, but an increased load factor on airplanes. The increase in passenger density decreases the likelihood of an empty

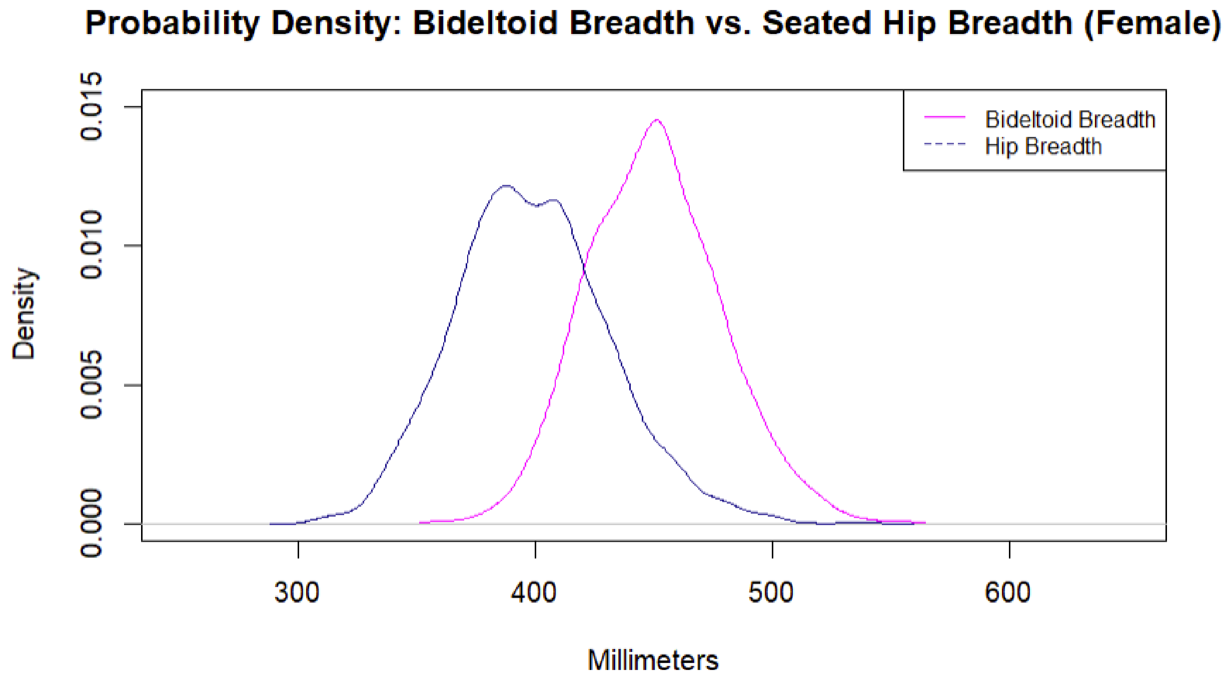

Figure 2.3: Comparison of bideltoid breadth and seated hip breadth measurements in ANSUR II military females using R Studio

seat next to a passenger, impacting their physical personal space and effect on psychological comfort. The airline focus on increased profit—leading to this increase in load factor—impacts not only larger individuals who may not be accommodated by a smaller seat, but even for men and women who fit in a seat and are disaccommodated by their shoulders. Disaccommodation and discomfort in airplanes, as the seat width continues to shrink, becomes not just an issue for larger individuals, but for everyone.

2.4 Comfort and Acceptability with Respect to this Experiment

The study presented in this thesis investigates comfort in terms of not only an individual's anthropometry, but their personal determination of how comfortable a space is. Each participant's rating of acceptability and sufficiency of width and space are recorded, establishing a hard-to-measure correlation as a result of the subjectivity. A variety of factors may influence someone's comfort in a space beyond just body size, including their interactions with other passengers or

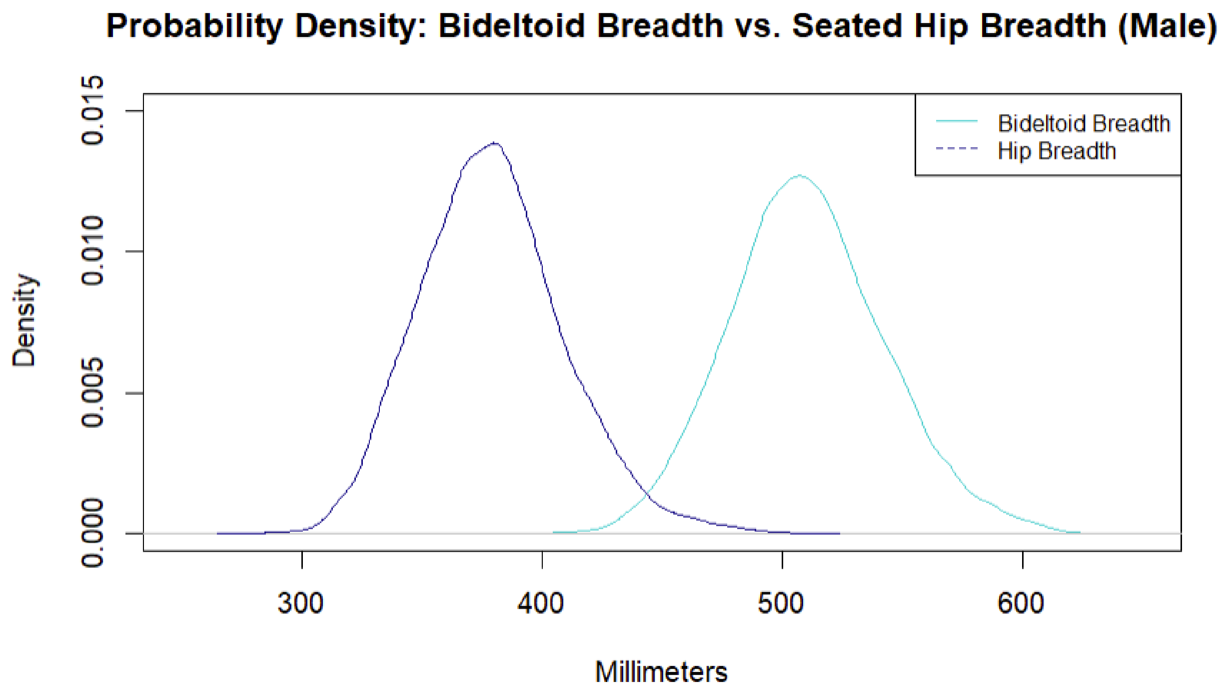

Figure 2.4: Comparison of bideltoid breadth and seated hip breadth measurements in ANSUR II military males using R Studio

personal experiences, making the examination of comfort with respect to an objective measurement essential in order to numerically determine comfort.

Currently, there is no standardized method to analyze the crossroads of comfort and acceptability; in a study that sought out to evaluate comfort in a bus seat, comfort was measured by arbitrary factors based on a participant's posture, EMG amplification of certain back muscles, and sensory engagement [23]. Participants were asked to simply evaluate the comfort of the seat with respect to the back of the seat—since acceptability was not connected to any of the measurements and the experiment was solely on comfort, no true method of an objective comfort determination could be determined. Current designers use 3D model databases to see how people with varying anthropometry fit into their design. However, no study has been done as of yet that involves actual people rating the comfort and acceptability of a seat—the 3D models don't have that ability. People are not just models with distinct anthropometry, but rather individuals with distinct personhood that impacts how they perceive comfort and acceptability. The experiment presented in this thesis aims to not only connect comfort and acceptability to one another, but also to bideltoid breadth, so that they may be analyzed together through a more standardized approach.

When it comes to the design of a particular human-occupied space or product in general, the accommodation and comfort factors are at the discretion of the designer. Since accommodation and comfort are currently distinct factors with no established relationship, the importance of this thesis lies in determining that relationship so that designers, through percentile-based analysis, may provide design recommendations based on accommodation levels that provide certain levels of comfort as well.

Chapter 3

Methods

In this section, the experimental methods are highlighted, including the MATLAB code and application used for each participant, the participant selection process and breakdown of “bins,” and the procedure of the experiment itself. At the point of this thesis submission, 50 individuals of varying body size and shape have participated to create a robust sample of data. The collected data consists largely of college-aged students with additional adult participants.

3.1 Equipment

The OPEN Design Lab in Engineering Unit C at Pennsylvania State University features numerous essential anthropometric measuring devices needed for this experiment. In addition to the anthropometric measuring tools, a data measuring tool was created as an app in MATLAB and presented on an iPad for each participant to enter their responses. Both the physical and the digital data measuring devices are elaborated upon in this section.

3.1.1 Measuring Tools in the OPEN Design Lab

Throughout all trials of the experiment, the following measuring tools were used to gather anthropometric data, measured in millimeters:

1. Scale with attached height rod
    (a) Used to take the weight (in kilograms) of the participant and their stature (height, in mm) measurement
2. Height measuring tape
    (a) Used to measure the seated height of the participant
3. Anthropometric calipers
    (a) Used to measure seated hip breadth for a participant
        i. Additional 3D-printed attachments for the calipers were created to accommodate larger participants.
    (b) Used to measure bideltoid breadth of a participant
4. L-shaped ruler
    (a) Used to measure buttock-knee distance of a seated participant

3.1.2 MATLAB Data Collection App

While the MATLAB code was being run, each participant saw the same application with rankings for the sufficiency and acceptability of the seat width and amount of space in addition to a sliding bar at the bottom of the app where the participant could rate their overall comfort (Figure 3.1). For ease of navigation, participants were given an iPad with the application on it to select their choices efficiently.

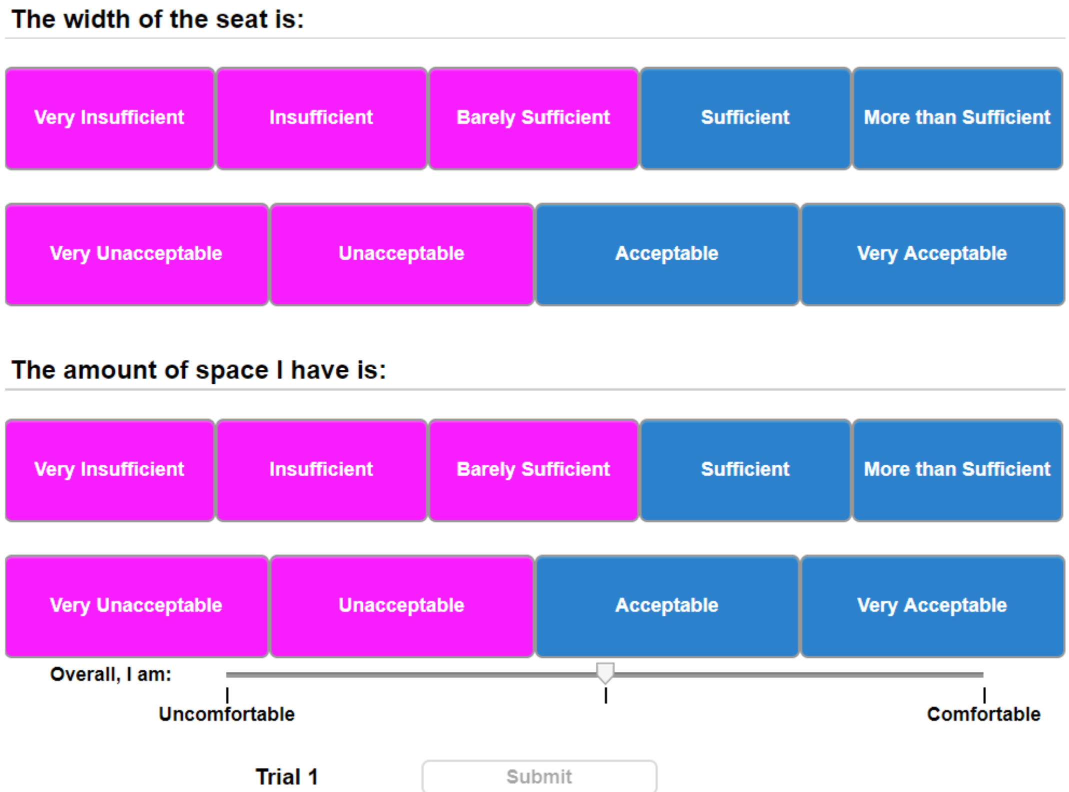

Figure 3.1: Data Collection App on MATLAB

3.2 Participant Bins and Selection

Throughout the participant selection process, the goal was to find participants with variations in stature and BMI to develop a well-rounded dataset. Between both male and female participants, there were nine bins for each sex (Table 3.1 and Table 3.2).

Participants were placed into 1 of 18 total bins based on their stature and BMI. The different

Table 3.1: Description of male bins (BMI vs. Stature) to be filled for the experimental procedure

	BMI < 25	BMI 25-35	BMI > 35
height < 66 in	A	B	C
height between 66 - 72in	D	E	F
height > 72 in	G	H	I

Table 3.2: Description of female bins (BMI vs. Stature) to be filled for the experimental procedure

	BMI < 25	BMI 25-35	BMI > 35
height < 60.5 in	J	K	L
height between 66 - 72in	M	N	O
height > 66.25 in	P	Q	R

groups for BMI were based on data from the Center for Disease Control (CDC), where a BMI under 25 is healthy, a BMI exceeding 35 falls into Class 2 (or Class 3) obesity, and the values between (25-30 and 30-35) fall into overweight and Class 1 obesity categories respectively [24]. For the purposes of this study, no one was classified as "underweight," which the CDC defines as anyone with a BMI under 18.5. Additionally, stature breakdowns were based on approximately the 25th and 75th percentile cutoffs for NHANES 2015-2018 data for both males and females [14]. The purpose of bin-filling in this study was to ensure a range of human anthropometry in both BMI and stature.

In order to develop a robust participant dataset, several methods were used to get enough participation. In the beginning stages, word of mouth for the initial trial runs and the first part of test data was the best way to gather the easier to fill bins, however, as the "averages" were quickly filled, a Google Form was created and sent out via GroupMe, social media, and different group chats to gather a higher volume of potential participants and as a result, more variation in the experimental population. Additionally, posters were hung up in both the early stages and later stages to gather a higher volume of participants from both the student and non-student population. As a result, an influx of both students and adults poured in, filling more bins than just the "average."

Most important in the participant gathering phase, especially in a large population of college students, was likely the financial compensation of $20 USD.

If participants were eligible to fill an unfilled bin, they would be contacted via email to confirm availability during one of their survey-determined time slots as well as confirming the location of the study. If participants were not eligible, they would be contacted letting them know their ineligibility. Eligible participants were scheduled in 45-minute time slots to account for running a few minutes behind, getting lost on the way, and for the experiment itself. The entire procedure, detailed below, took around 35 minutes per participant.

3.3 Procedure

The general outline for the procedure is as follows:

1. Follow introductory procedure
   (a) Explain the research procedure and consent
   (b) Ask introductory questions with answers entered in MATLAB
   (c) Take anthropometric measurements
2. Complete all 35 trials
   (a) No boundary conditions (randomized for 5 trials)
   (b) Randomized boundary conditions/widths for 25 trials
   (c) No boundary conditions (randomized for 5 trials)
3. Debrief and pay participant
4. Backup and analyze data

The experimental procedure was approved by an appropriately constituted Internal Review Board (IRB) to ensure proper protection of human test subjects.

3.4 Introduction

When a participant arrives at their scheduled time, they are invited into the OPEN Design Lab, are asked to take a seat if they would like, and to read over and sign a consent form. This consent form highlights the voluntary participation in the study, importance of the study, and participant rights according to the Institutional Review Board (IRB). After signing the consent form and asking questions they may have, the MATLAB code is started and the trial begins. A research assistant enters the trial number, whether the participant is a test or trial, then reads the following statement out loud to the participant:

> *This experiment will take no more than 45 minutes. At any point in the procedure, you may choose to end the experiment if you feel uncomfortable. If you are uncomfortable with the physical requirements of the task then you should not participate. We will use this data in future publications on ergonomics. Any reporting of the data will be completely anonymous. Feel free to ask questions at any time.*

After this phrase is read the the participant understands their verbally-explained rights, the following general questions are asked regarding the participant:

- What is your gender?
- What is your age?
- What is your height (in.)?
- What is your weight (pounds)?
- What is your dominant hand?
- How many times do you fly per year?

Once these questions are answered, the participant is told to remove their shoes and any coat or sweatshirt they may be wearing and is directed into the lab space where the following measurements will be taken (in millimeters or kilograms):

- Stature
- Mass

- Sitting height
- Seated hip breadth
- Bideltoid breadth
- Buttock-knee distance

Once a participant's measurements were collected, they were read the following statements:

Now we will move on to the next stage where you will be sitting in a model airplane seat. You will be given instructions to read that explain each part of the experiment. Please read these instructions carefully.

Please sit in the airplane seat model. Throughout the experiment, the research assistant will be changing the seat width dimensions by moving the armrests side to side. After every new dimension, please complete the online survey. The questionnaire will be administered by a data collection platform on an iPad. This process will be repeated several times with different armrest positions controlling the width of the seat.

Once the research assistant has read the above statements out loud, the participant is handed the iPad and walked through each of the questions as shown in Figure 3.1. Due to some test trial participants failing to complete the slider ranking comfort at the bottom of the screen, research assistants found that directly pointing the slider out led to successful completion of that essential question. After the adjustment of the airplane seat apparatus for the first Trial 1, the participant is asked to take a seat and enter their responses to questions on the provided iPad and the experiment commences.

3.5 Experimental Trials

During the experiment itself, 35 total trials are run with varying seat widths and boundary conditions to gauge both the comfort and acceptability as reported by each participant.

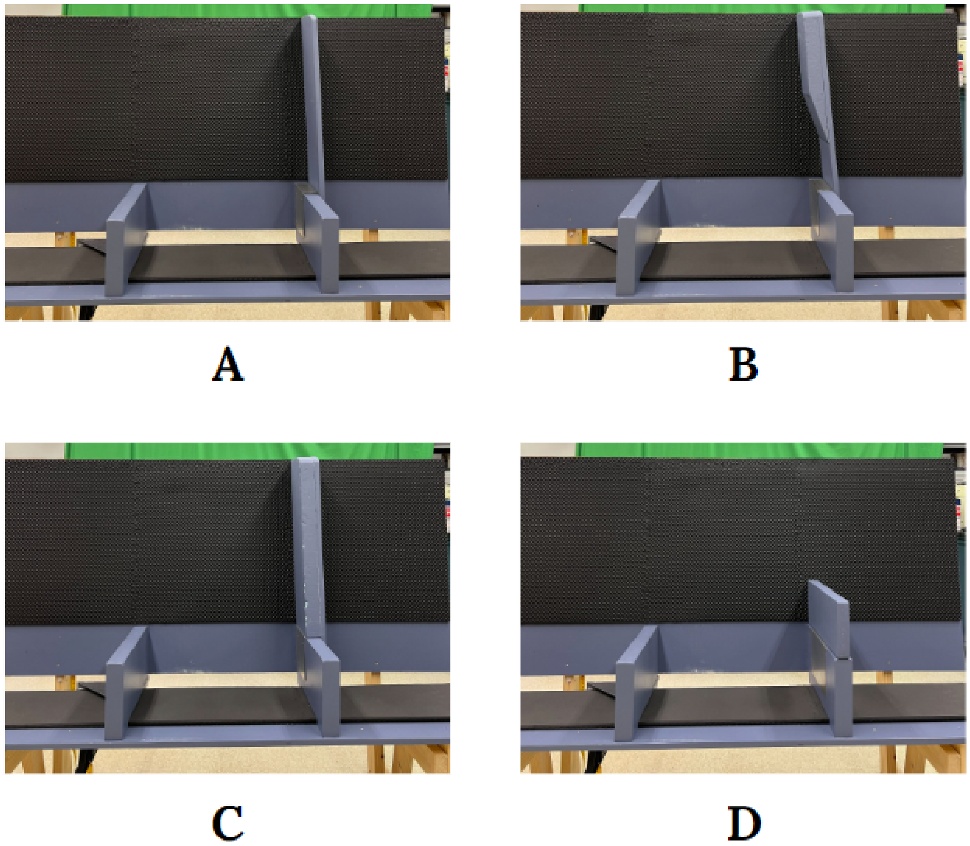

Figure 3.2: One-sided boundary conditions - passenger's left side

3.5.1 Boundary Conditions

This experiment was designed to simulate real-life scenarios a passenger would experience in an airline seating through the use of physical boundary conditions. When a trial occurred with changing width and no boundary condition, a passenger sitting with both armrests available and no one next to them was simulated. One-sided boundary conditions (see Figure 3.2 and Figure 3.3) represents another passenger next to a participant; Condition A represent another passenger who does not infringe upon bideltoid space or armrest space, Condition B recreates a condition where bideltoid space is infringed upon, but armrest space is not, Condition C poses a case where both bideltoid and armrest interaction occurs, and Condition D creates solely armrest interaction.

The same cases are created on both the right and left sides separately, as well as together in two-sided boundary condition (see Figure 3.4) representing passengers on either side. The purpose

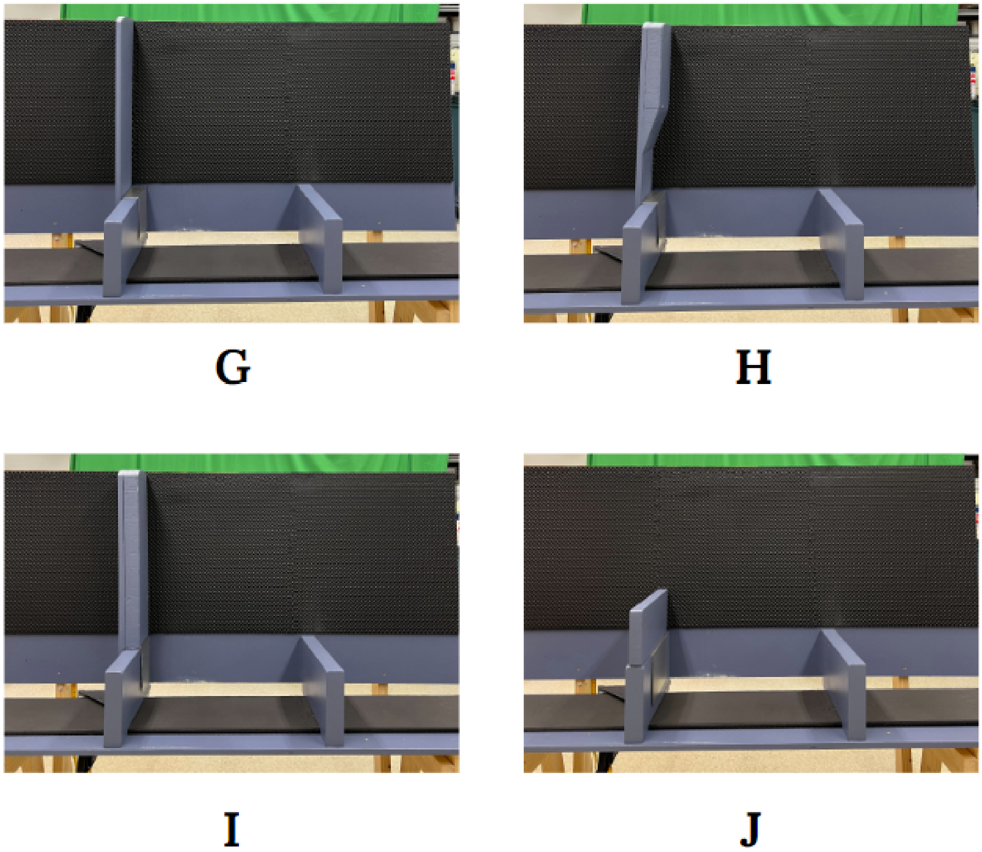

Figure 3.3: One-sided boundary conditions - passenger's right side

of using both one and two-sided boundary conditions was to gain insight into conditions where a participant's bideltoid breadth is interacted with from both sides, creating additional understanding on how different cases impact comfort.

To gather more realistic data with a real human passenger rather than a physical boundary condition, research assistants were used. Figure 3.5 shows the research assistants in a seated position creating both bideltoid and armrest interaction with the participant.

Due to one of the research participant's graduation, the last part of experiments were completed with a different male human boundary condition. However, each research assistant sat in the same manner every time. Throughout the experiment, participants frequently asked about what each boundary condition represented, so in later trials a research assistant would verbally explain the designated meaning to ensure participant understanding of the trial.

Throughout the experiments, participants were encouraged to take their time to make a judge-

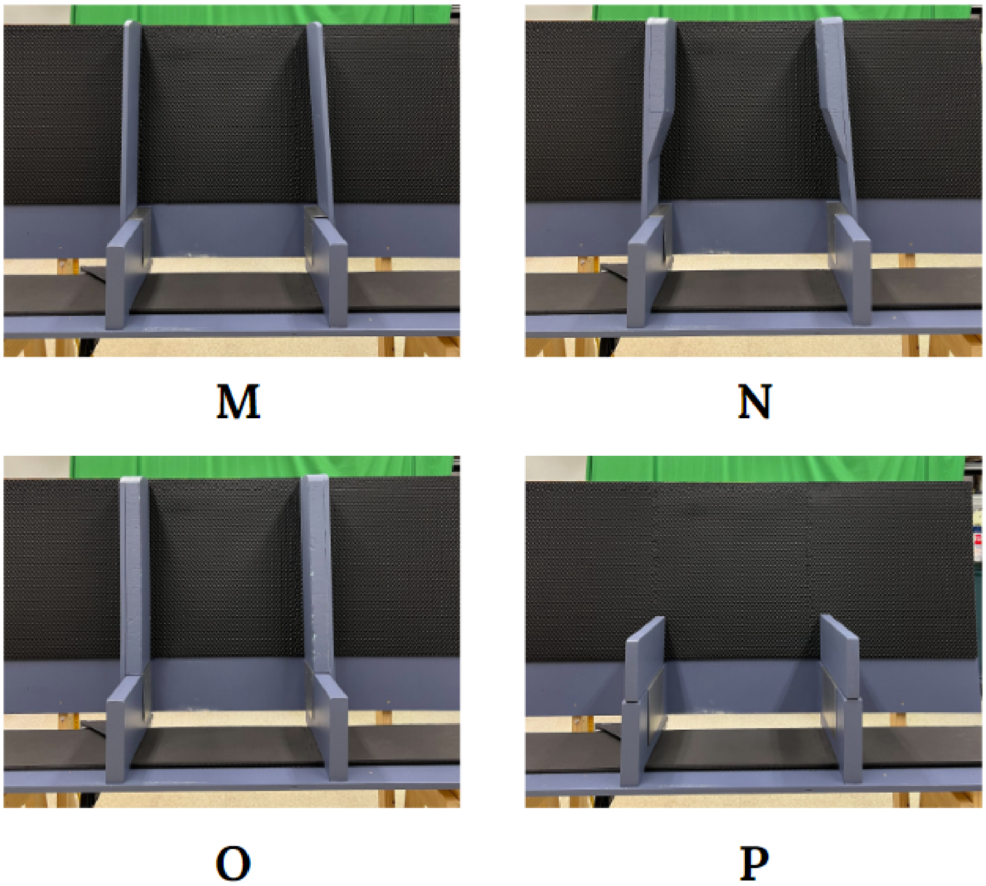

Figure 3.4: Two-sided boundary conditions

ment; although research assistants wanted to encourage a steady pace, trials occasionally changed by only a few millimeters, thus, careful note of the conditions were encouraged for participants. Additionally, as participants went through the trials, research assistants occasionally checked in with them to confirm which trial the experiment was on as well as to double check that they were completing the slider ranking comfort. Out of 35 MATLAB-randomized trials, the following breakdown occurred:

- (10) Trials with no boundary conditions
- (16) Trials with one sided boundary conditions
- (9) Trials with two sided boundary conditions

In this experiment is that the five trials at the beginning (1-5) with no boundary conditions are repeated at the end of the experiment (31-35) in a different order to determine the drift in a participant's comfort rankings, comparing them to analyze an individual's variability in their measurements.

3.5.2 Seat Width

Although there were 35 trials throughout the experiment, the seat widths were repeated as follows:

- Seated hip breadth - 25 mm (12 trials)
- Seated hip breadth (12 trials)
- Seated hip breadth + 25 mm (6 trials)
- Seated hip breadth + 50 mm (2 trials)
- Bideltoid breadth (1 trial)
- 432 mm (2 trials)

The measurement of 432 mm is based off of the standard measurement for seat widths in airplanes. After the successful completion of all 35 trials, participants were told they had completed the procedure, were asked to sign a sheet to confirm that they had received the correct compensation amount of $20 USD, and thanked for their participation.

3.6 Data Analysis

After each participant, data was exported to a spreadsheet to ensure a backup file different than the saved MATLAB data. After the data gathering stage was completed, 56 individuals had participated in the experiment, each providing valuable insight into their personal perception of acceptability, space, and comfort. Full details of the analysis will be detailed in the results of Chapter 4.

3.6.1 Experimental vs. General Population

The participant dataset aims to be representative of a larger population who travels in airplanes. Figure 3.6 and Figure 3.7 depict representations of not only the most recent National Health and Examination Survey (NHANES) BMI distribution, but the distribution of the experimental dataset of participants.

As a result of the size of the experimental population, the spread is similar, but not identical, to the spread of the large-scale population presented in the NHANES data. Using an experimental dataset that is representative of a large-scale dataset enables the study to produce results that will provide better design recommendations for an entire population.

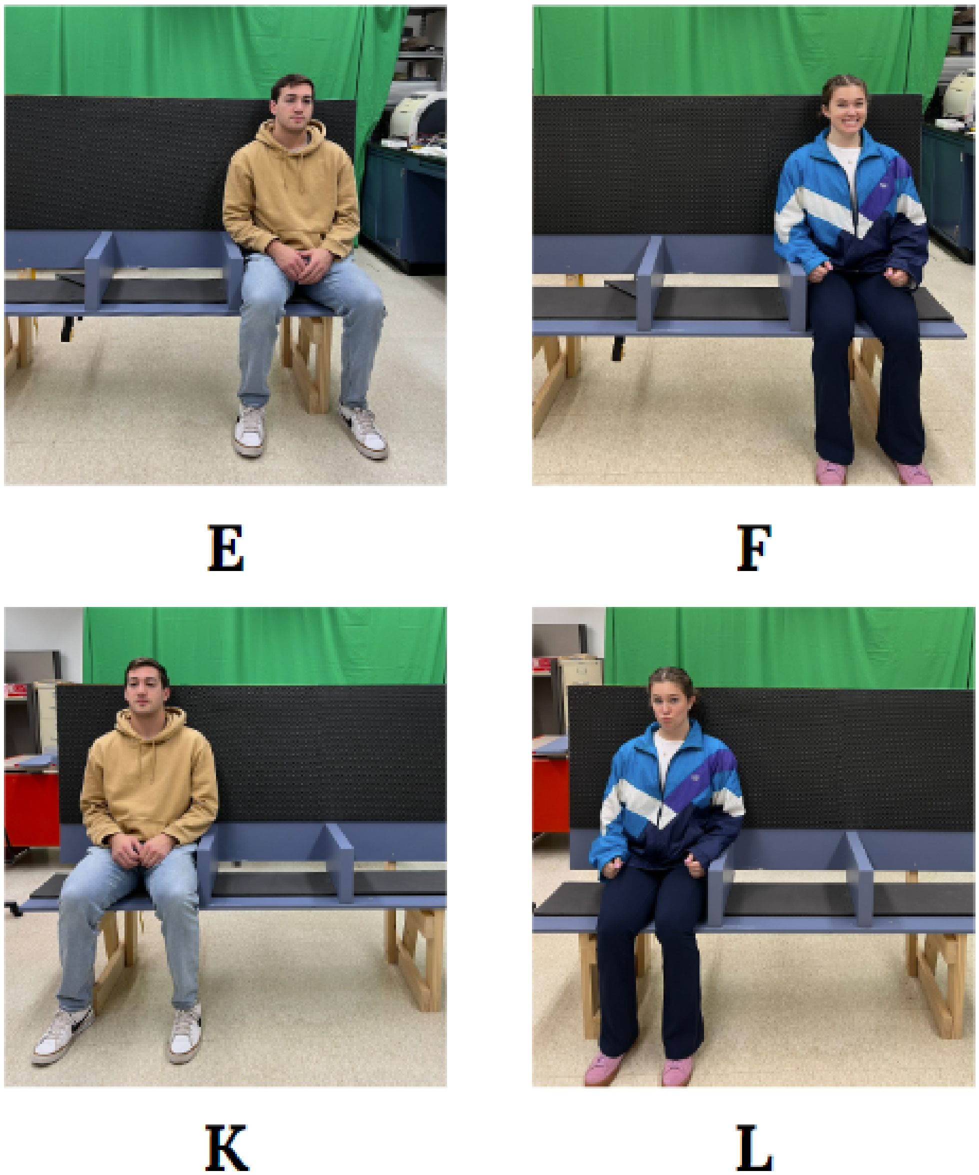

Figure 3.5: Human boundary conditions

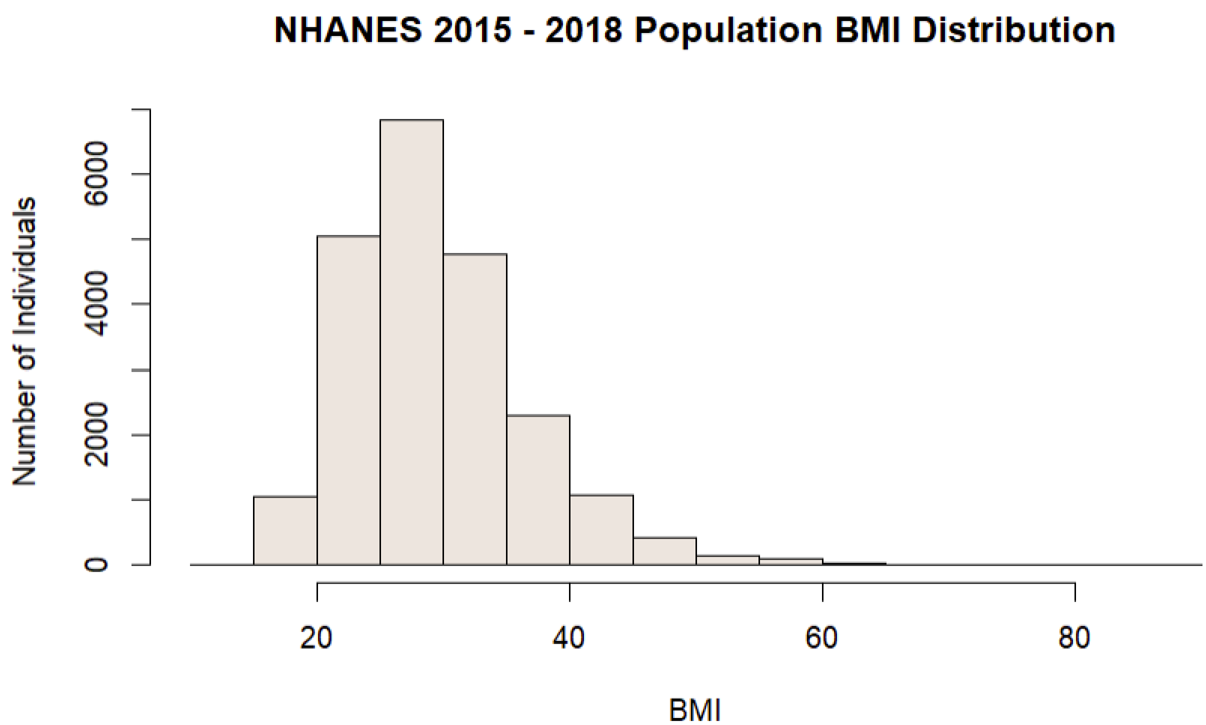

Figure 3.6: BMI distribution for a large United States population dataset in NHANES 2015-2018, created using R Studio

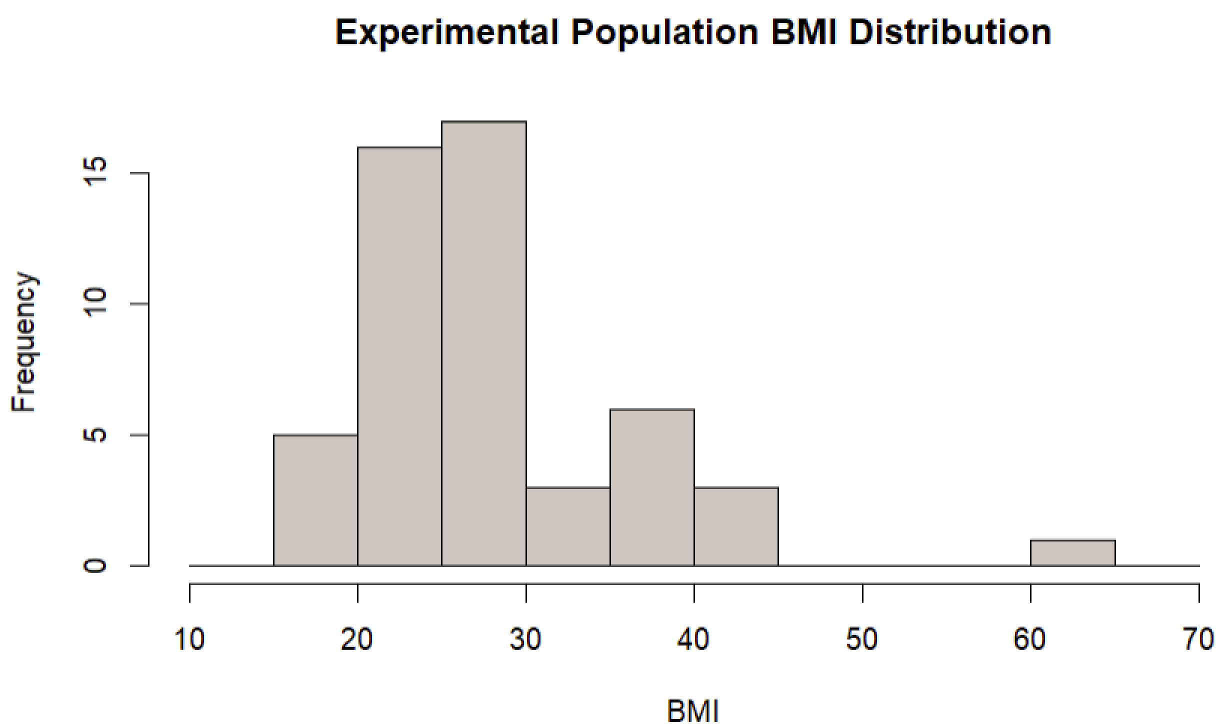

Figure 3.7: BMI distribution for an experimental dataset of civilians in the experiment presented in this thesis, created using R Studio

Chapter 4

Results

This section highlights different analyses run using R Studio, a programming language designed for statistical computing. Using this software, different datasets were used including the ANSUR military personnel and NHANES 2015-2018 datasets as baseline population data for a realistic civilian population. Then, using the data collected in the 50 total human trials conducted, different relationships related to bideltoid breadth will be examined in addition to establishing a relationship between comfort and acceptability using real human fit trials.

With 18 total bins between male and female participants, which included 3 individuals per outer bin and 5 in the center bin, the goal was to gather 58 individuals and fill the bins. In the end, 50 individuals were gathered, however, some of the bins were unfilled and others were overfilled. The final participant breakdown is detailed in Table 4.2 and Table 4.1.

A majority of the bins were able to be filled, or overfilled in some cases. Bins which were left untouched were not ideal, but rich information is presented in these data due to the volume of participants tested.

Table 4.1: Final male population for the male BMI vs. stature bins

Height	BMI < 25	BMI 25-35	BMI > 35
< 60.5 in	3	1	0
60.5 - 66.25in	5	5	3
> 66.25 in	3	2	2

Table 4.2: Final female population for the female BMI vs. stature bins

Height	BMI < 25	BMI 25-35	BMI > 35
< 66.0 in	2	5	0
66 - 72in	6	2	3
> 72 in	3	3	2

4.1 Acceptability of a Standard Airplane Seat

Although the standard seat width in existing airplanes is 432mm, this type of seat is different than other kinds of non-airline seating. For example, most Economy class airplane seats are narrower than the standard used for office furniture design – the HFES 100-2007 standard of armrest width in furniture design is 460mm apart [25]. Regarding the ANSI/HFES 100-2007 standard, this width measurement is intended for office furniture rather than for airlines. Additionally, the standard distance between armrests (432mm) is based off of ANSUR II data for military personnel, an inclusive, yet specific dataset, and not more recent civilian data. The data from a 1996 survey specific to military personnel contains different anthropometry, especially in BMI, than a civilian population found in either NHANES or within the experimental dataset in this thesis. A preliminary analysis was completed detailing the civilian accommodation levels of males, females, and overall accommodation.

Airplane seat design should consider both hip and shoulder breadth; since bideltoid breadth is nearly always wider than seated hip breadth, the accommodation must be based off of the armrest width rather than the seat width to accommodate the shoulders of passengers. Another design

Table 4.3: Bideltoid breadth accommodation based on standard airplane seat and ANSI/HFES recommendation

Seat Widths	Male	Female	Overall
432mm	2.6%	43.9%	23.2%
460mm	13.1%	69.8%	41.5%

consideration besides the width of the armrest is the interaction between passengers. As a result of bideltoid breadth being wider than seated hip breadth, passenger interaction is likely if only seated hip breadth is taken into account in a design. The ANSI/HFES 100-2007 standard sets a baseline width for office seating, but the design for office seating is designed for individual use compared to packed airplanes. Using the VFT tool called the Multivariate Accommodation Testing Tool, accommodation rates for a civilian dataset for both 432mm and 460mm are shown in Table 4.3.

Knowing the accommodation rates for the most recent population dataset, 432mm as a standardized seat measurement is clearly inadequate. To elaborate on this initial information, we are able to use the experimental participant data for 432mm in order to determine both the acceptability and comfort of this measurement. Ratings of sufficiency and acceptability will be as follows:

- Sufficiency
  - 1: Very Insufficient
  - 2: Insufficient
  - 3: Barely Sufficient
  - 4: Sufficient
  - 5: Very Sufficient
- Acceptability
  - 1: Very Unacceptable
  - 2: Unacceptable

- 3: Acceptable
- 4: Very Acceptable

Additionally, overall accommodation will be rated on a scale of comfort from 0 (uncomfortable) to 100 (comfortable), The numerical categorization of subjective qualities of subjective quantities will allow a previously undetermined relationship to be determined between these variables.

4.1.1 Experimental Participant Data

After uploading the human participant data into R Studio, some preliminary metrics could be established for this experimental population. The minimum, maximum, and average values for stature and bideltoid breadth are shown in Table 4.4. Additionally, the minimum BMI for the full population was 17.7, the maximum was 61.1, and the mean was 27.8. The distribution of the population is better described visually in Figure 4.1 and Figure 4.2 (vertical lines showing minimum, maximum, and average values on plot).

Table 4.4: Stature and bideltoid breadth distribution for male and female participants (millimeters)

	Male	Female
Minimum Stature	1609	1415
Maximum Stature	1950	1795
Mean Stature	1760	1615
Minimum Bideltoid Breadth	402	390
Maximum Bideltoid Breadth	742	560
Mean Bideltoid Breadth	509	442

Although there is certainly a broad range of values for bideltoid breadth and stature, a better way to showcase an anthropometric relationship is through BMI. A more linear relationship shown in Figure 4.3 and Figure 4.4 highlight the importance of bideltoid breadth within the scope of secular body trends of BMI increasing over time in a population.

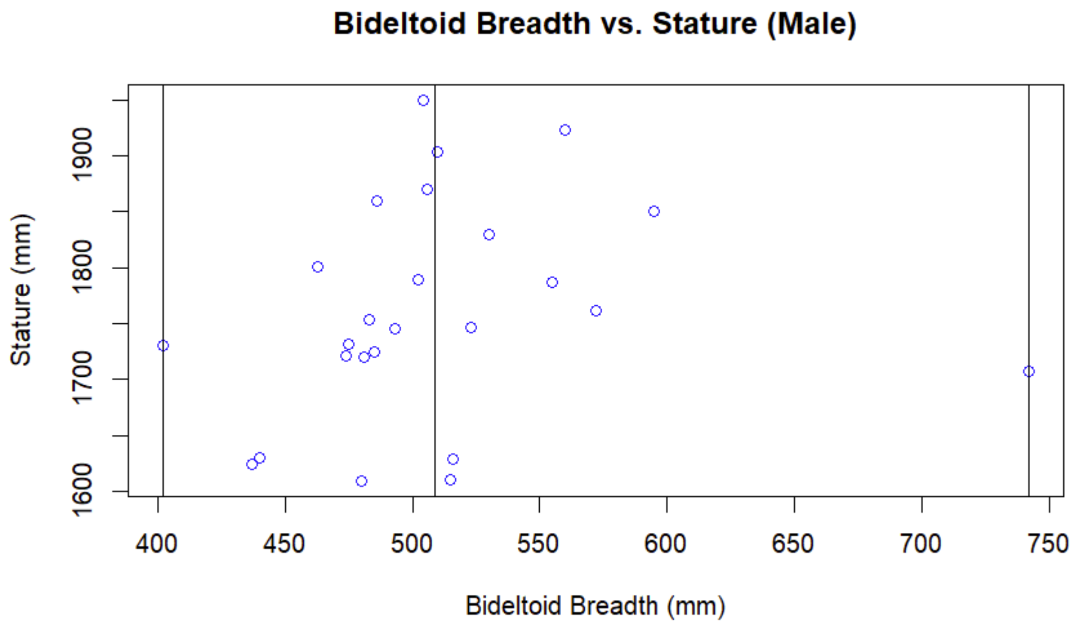

Figure 4.1: Bideltoid breadth vs. stature for the experimental population - male

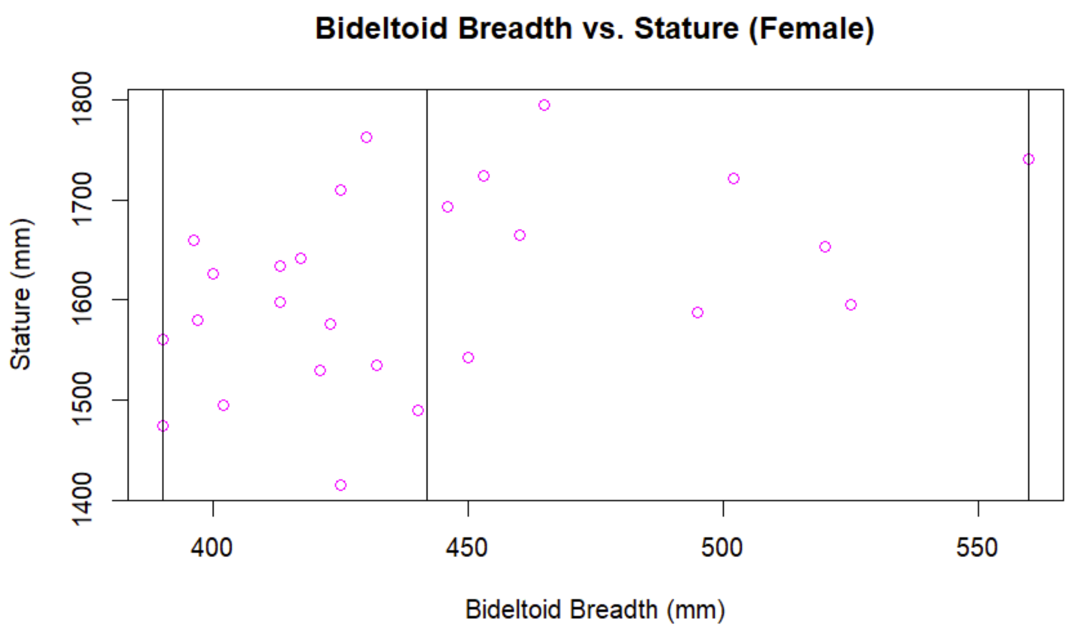

Figure 4.2: Bideltoid breadth vs. stature for the experimental population - Female

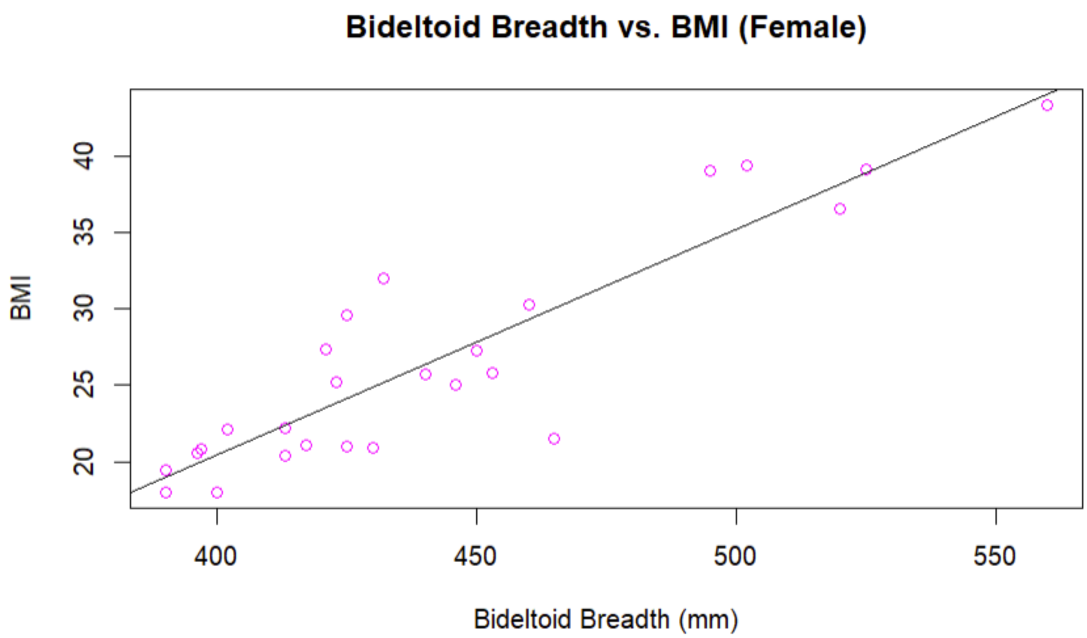

Figure 4.3: Bideltoid breadth vs. BMI for the experimental population - female

4.2 Acceptability and Sufficiency of Seat Width and Space

After determining different anthropometric relationships within the human participant data, more concrete data were able to be gathered from their experimental inputs regarding space, width, and overall accommodation. This thesis examines different relationships between bideltoid breadth, space, and width, as well as overall accommodation. The figures in this section detail distributions with certain ratings for width acceptability, width sufficiency, space acceptability, space sufficiency, and overall comfort. Several cases will be examined for acceptability and sufficiency when bideltoid breadth *exceeds* the boundary condition seat width for two-boundary condition cases and bideltoid breadth *equals* seat width in the case of one-sided boundary conditions.

Additionally, one-sided cases will be examined to determine acceptability and sufficiency of width and space in a false boundary condition case; although the one-sided cases do not feature as much bideltoid breadth interaction as the two-sided cases, the purpose is to be able to examine these cases with respect to the *real* human boundary conditions.

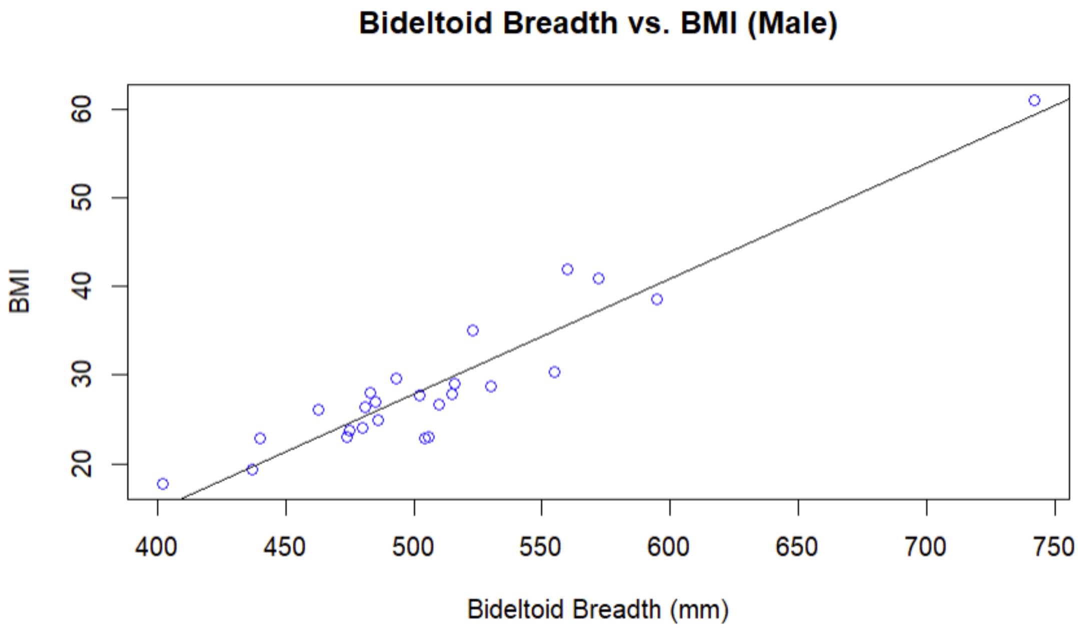

Figure 4.4: Bideltoid breadth vs. BMI for the experimental population - male

4.2.1 Acceptability and Sufficiency with Respect to Bideltoid Breadth in a Two-Boundary Condition Scenario

In the cases detailed in this section, experimental data were reduced to seating conditions such that the width between armrests was *greater than* an individual's bideltoid breadth. These individuals were analyzed in trials featuring dual boundary conditions as wide as the seat width (conditions N and O), which feature other "passengers" encroaching on both armrest and personal space. Conditions M and P are not used; although they are two-sided boundary conditions, they lack bideltoid breadth interaction, whereas Conditions N and O feature bideltoid breadth interactions. The sufficiency and acceptability ratings for these conditions are shown in Figures 4.5 - 4.8.

Shown in Figure 4.5 is a histogram of the occurrence of a certain acceptability rating 1-4 (y-axis) and the particular rating it falls under (x-axis) from a scale of 1 (Very Unacceptable) and 4 (Very Acceptable). From the figure, participants do not trend toward a Very Acceptable width, illustrated by the lack of frequency in that column. Most of the spread falls under Acceptable, Unacceptable, or Very Unacceptable in the case of width acceptability. There is no clear relation-

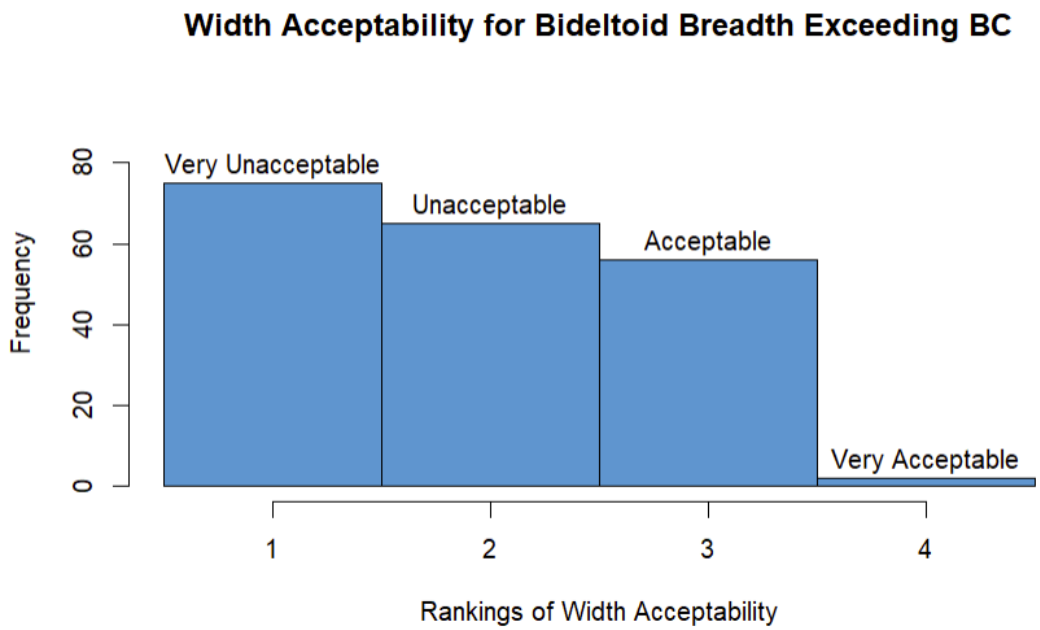

Figure 4.5: Acceptability rating of seat width with respect to bideltoid breadth in a two-boundary experimental condition

ship with bideltoid breadth, but the histogram indicates a trend in more unacceptable widths in two-boundary condition cases.

Figure 4.6 details the distribution in width sufficiency ratings on a scale of 1-5 (x-axis) from a scale of 1 (Very Insufficient) and 5 (More than Sufficient). In this case, a trend can be seen in the histogram; there is a high frequency of Very Insufficient width rating and a very low frequency of a More than Sufficient rating, showing that in the case of two-boundary conditions in which shoulder width exceeded seat width, participants overall did not view it as a sufficient amount of width.

For Figures 4.7 and 4.8, the space acceptability and sufficiency ratings were detailed on the x-axis. In each case, the amount of space was considered to rarely fall under Very Acceptable or More than Sufficient. Each graph shows a trend toward both Very Unacceptable/Unacceptable and Very Insufficient/Insufficient. When it comes to space sufficiency and acceptability in two-boundary condition cases throughout this experiment, very few people viewed the amount of space they had as enough. This data for two-boundary conditions in which individuals have bideltoid

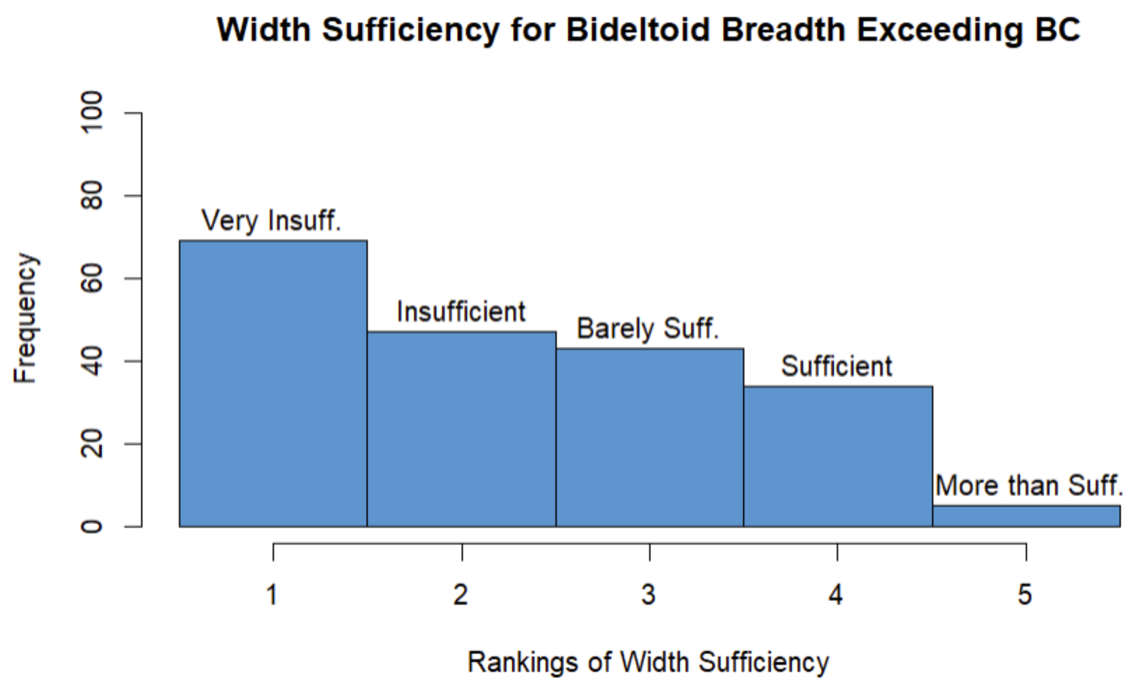

Figure 4.6: Sufficiency rating of seat width with respect to bideltoid breadth in a two-boundary experimental condition

breadth wider than the seat width corroborates with the knowledge that passengers are affected both psychologically and physically by other passengers in their personal space, hence the issue of both increased load factor and decreased seat width in airplanes.

4.2.2 Acceptability and Sufficiency with Respect to Bideltoid Breadth in a Single-Boundary Condition Scenario

In the previous cases, the relationship between sufficiency and acceptability of width and space were examined in two-boundary conditions (physical barriers in the experimental setup) with data limited to cases that featured a narrower seat width than the participant's bideltoid breadth.

In the following cases, *all* seat width cases will apply, and one-sided boundary conditions will be examined, specifically those that interact with the shoulders (conditions B, C, H, and I). Since the focus on this thesis revolves around bideltoid breadth, the data related to bideltoid breadth passenger interactions were examined rather than all conditions (one-sided conditions of A, D, G,

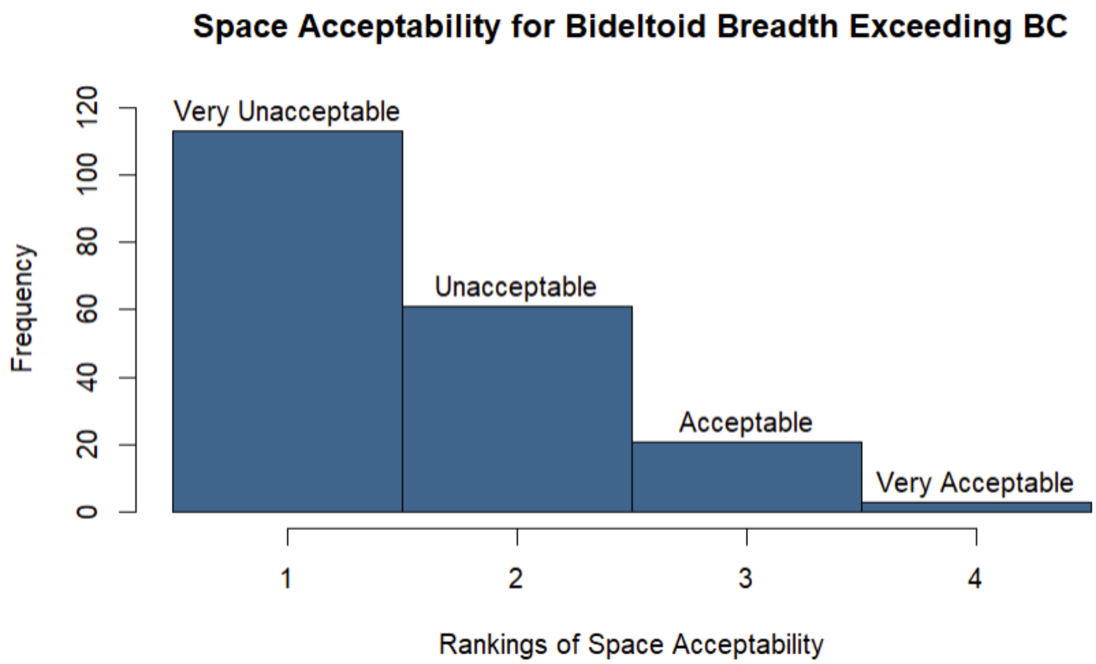

Figure 4.7: Acceptability rating of space with respect to bideltoid breadth in a two-boundary experimental condition

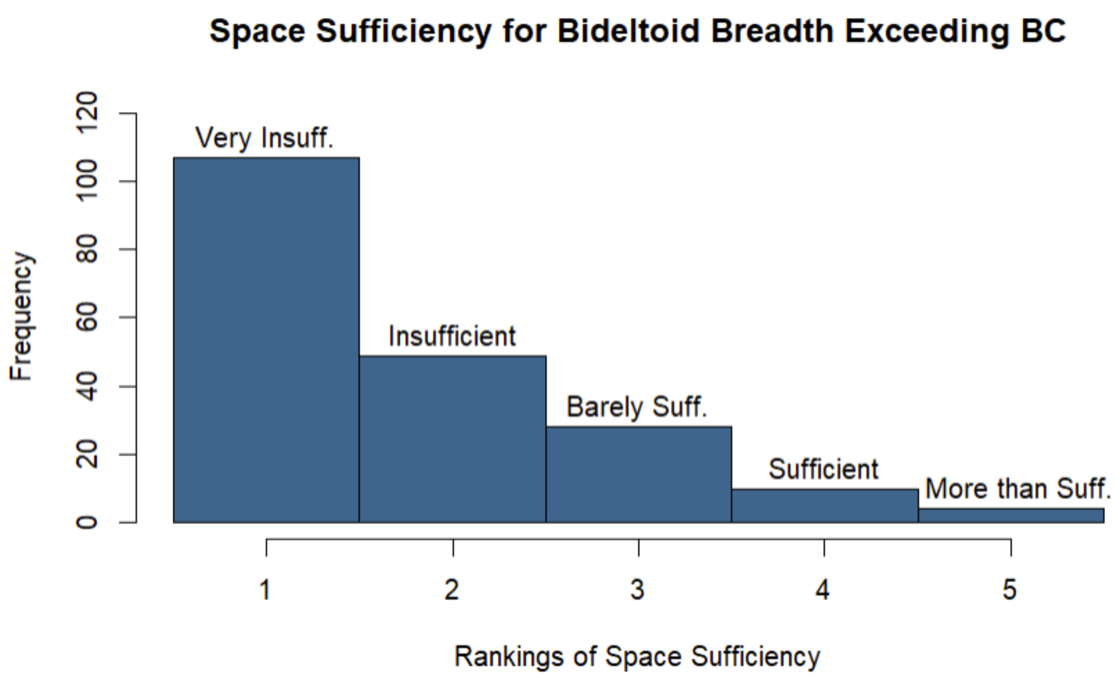

Figure 4.8: Sufficiency rating of space with respect to bideltoid breadth in a two-boundary experimental condition

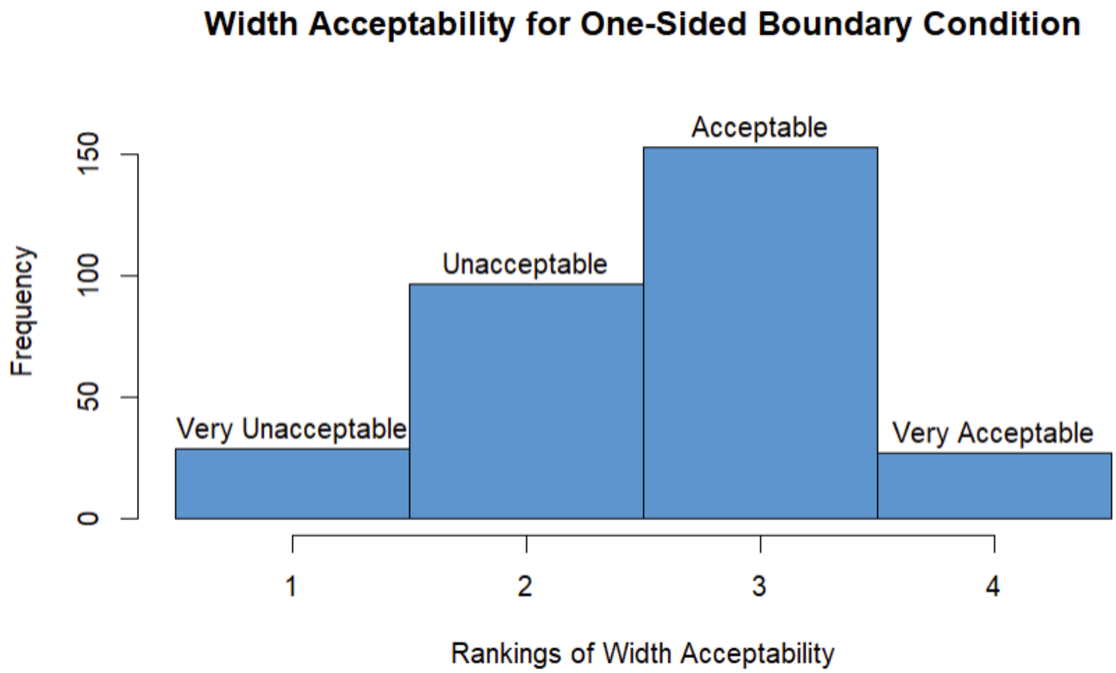

Figure 4.9: Acceptability rating of seat width in one-sided boundary conditions of all boundary widths

and J were omitted). The cases for acceptability and sufficiency of both width and space with a one-sided boundary condition are shown in Figures 4.9 - 4.12.

When examining Figure 4.9, the ratings of width acceptability fall on the x-axis and the frequency of each rating falls on the y-axis. In the case of a one-boundary condition, the most commonly reported answer is an Acceptable width. Compared to a two-sided boundary condition where the most commonly reported response is a Very Unacceptable, a one-sided condition clearly provides a more acceptable width to participants.

Figure 4.10 features a histogram detailing the frequency (y-axis) of the width sufficiency ratings 1-5 on the x-axis. From observation of the figure, a trend leans toward Sufficient. Few participants rated either extreme of Very Insufficient or More than Sufficient. As a result, it can be concluded that participants generally felt satisfied with width in a one-sided condition. However, the width sufficiency ratings for the two-boundary condition trended toward the left; responses of Very Insufficient were the most common, followed by Insufficient and Barely Sufficient also being commonly reported. The presence of another boundary condition (and another passenger in the

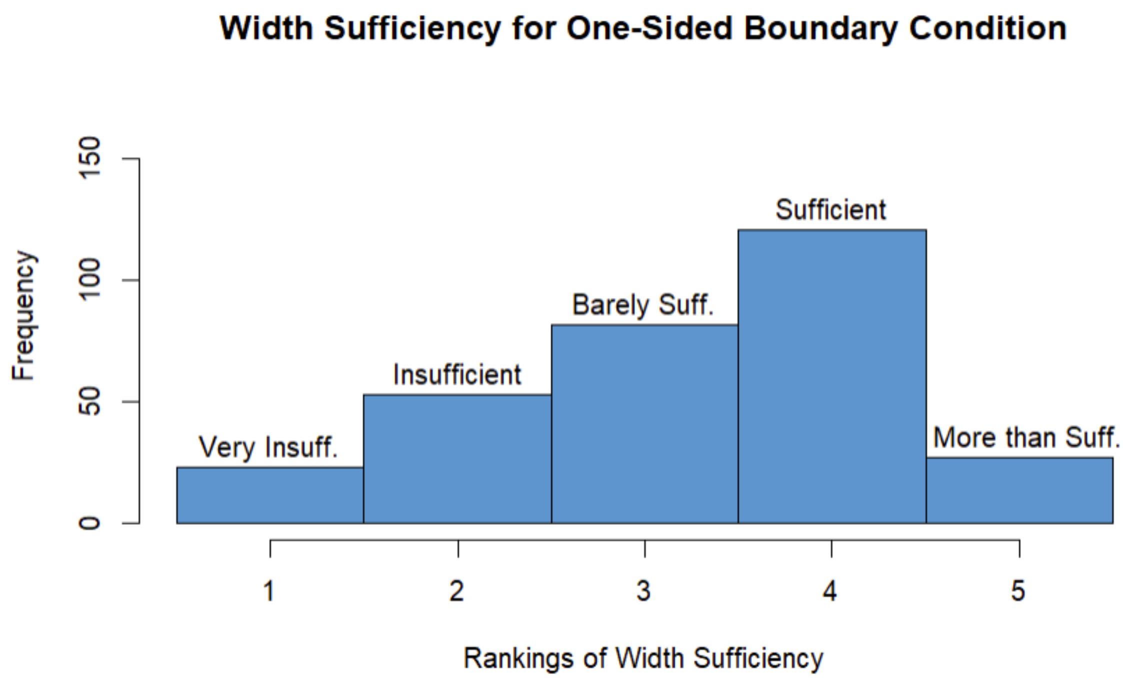

Figure 4.10: Sufficiency rating of seat width in one-sided boundary conditions of all boundary widths

real world) impacts the rating of width sufficiency.

The rating for space acceptability are shown on the x-axis of Figure 4.11. Illustrated in this histogram is a trend toward the "middle" responses of Acceptable and Unacceptable. As a result, a clear conclusion cannot be drawn except that participants were neither completely satisfied nor completely unsatisfied with the amount of space they had in this scenario. In the case of a two-boundary condition shown in Figure 4.7, the trend is again toward the left region of the graph with a considerable distribution falling into the Very Unacceptable rating. Although participants did not have responses that fell on either end of the graph, the conclusion may still be drawn that a one-sided condition is more favorable than a two-sided condition with respect to space acceptability.

Finally, Figure 4.12 details the distribution of one-sided boundary condition results for space sufficiency ratings. In this figure, a clear result is shown toward a Barely Sufficient with the other most common as Sufficient and Insufficient. This result is inconclusive, but again indicates that participants did not experience either Very Insufficient or More than Sufficient levels of space; a generally neutral response was evident from space sufficiency data of a one-sided boundary con-

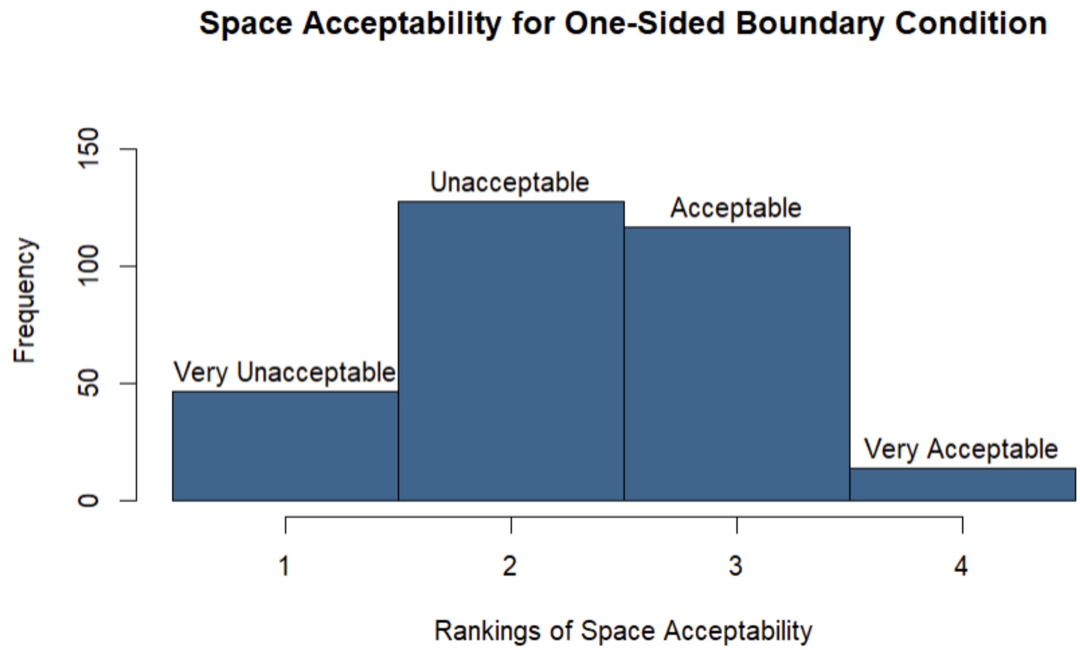

Figure 4.11: Acceptability rating of space in one-sided boundary conditions of all boundary widths

dition. Looking back at the two-sided case in Figure 4.7, a leftward trend occurs with a clearly common result of Very Insufficient amount of space. Once again, in spite of the lack of tail-end responses, the case of a one-sided boundary condition displays participant favor over a two-sided boundary condition in terms of space sufficiency. This conclusion ties into the real-world case of increased load factor in airplanes, where a more densely-packed plane means that passengers are more likely to be seated next to one another, leading to greater levels of perceived space insufficiency.

4.2.3 Acceptability and Sufficiency with Respect to Bideltoid Breadth in a Human Passenger Scenario

After establishing interactions between both two-sided and single-sided boundary conditions (physical barriers in the experimental setup), the relationship between a human participant and human boundary condition can be comparatively examined. Within the 35 trials, 4 total single-sided human boundary conditions occurred with both a male and female research assistant seated

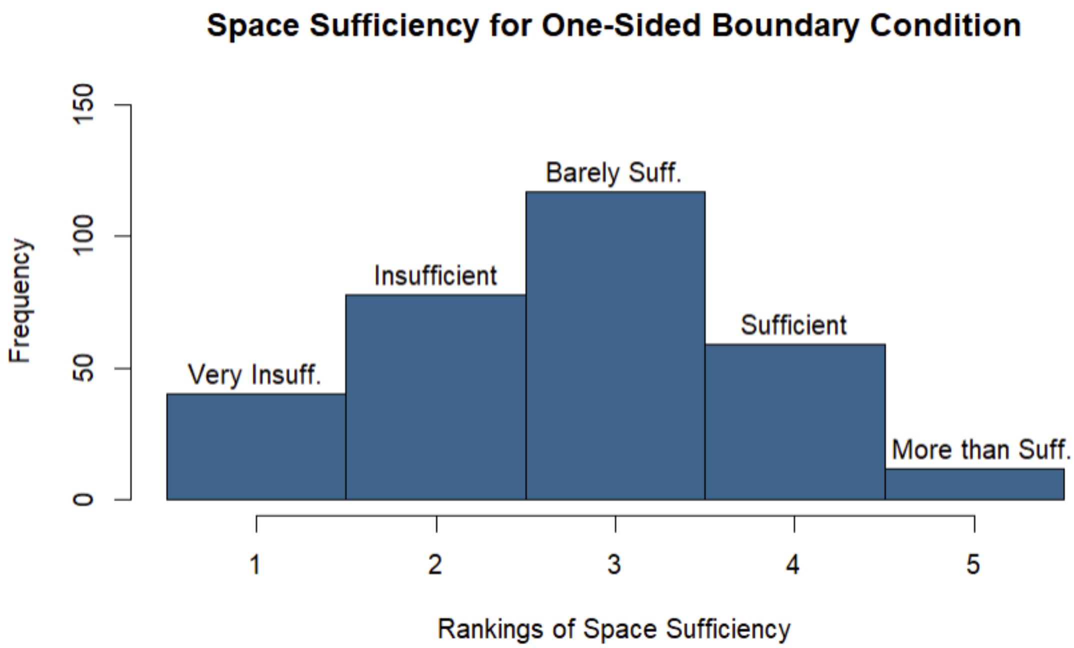

Figure 4.12: Sufficiency rating of space in one-sided boundary conditions of all boundary widths

next to someone. The cases examined in this section feature all human trials (trials E and K for a male boundary condition and F and L for a female boundary condition) *without* limiting the seat width. Although the cases before (N and O) feature physical boundaries representing other passengers, the addition of human boundary conditions is important to introduce personal space with respect to another person encroaching on space (both with bideltoid breadth and armrest encroachment). The cases for acceptability and sufficiency of both width and space with a human boundary condition are shown in Figures 4.13 - 4.16.

In Figure 4.13, a histogram illustrates the frequency of occurrence (y-axis) with respect to the ratings of width acceptability (x-axis) from a scale from 1 to 4 (Very Unacceptable to Very Acceptable). This figure highlights the spread of the width acceptability ratings for all human trials within the data. In the case of width acceptability, there is the most frequency of Acceptable, the fewest in Very Acceptable, and the rest falling under Unacceptable/Very Unacceptable. In the one-sided boundary condition case, the most frequency also occurs within the Acceptable column, indicating that the width acceptability of a one-sided boundary and a human boundary is not perceived as different by participants.

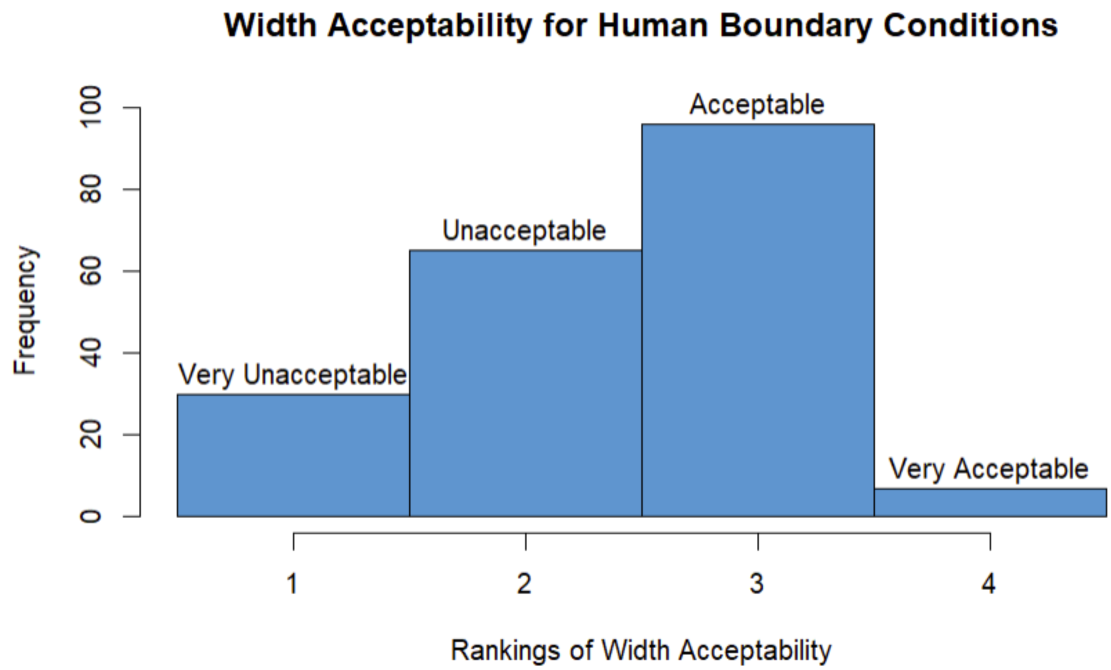

Figure 4.13: Acceptability rating of seat width in human boundary conditions of all boundary widths

The data in width acceptability follows similar trends as Figures 4.14 (width sufficiency). The least amount of frequency occurred in the More than Sufficient category for width sufficiency, and the most fell into both Sufficient and Barely Sufficient, indicating an overall, but not entirely positive result. In Figure 4.10, the most common result fell into Sufficient, again indicating similar responses between a real person as a boundary and a physical barrier.

In the case of space acceptability shown in Figure 4.15, Unacceptable and Acceptable were the most commonly reported. Figure 4.11 features the same common results, indicating that between a real passenger on one side and a false barrier, there is not a difference in acceptability between the two cases.

When it comes to space sufficiency of a human boundary condition (Figure 4.15), most people said the space was either Insufficient or Barely Sufficient. Very Insufficient and Sufficient were equally reported, and nearly no participants responded with More than Sufficient. The space sufficiency of the one-sided boundary (Figure 4.12) fell mostly in Barely Sufficient and largely in

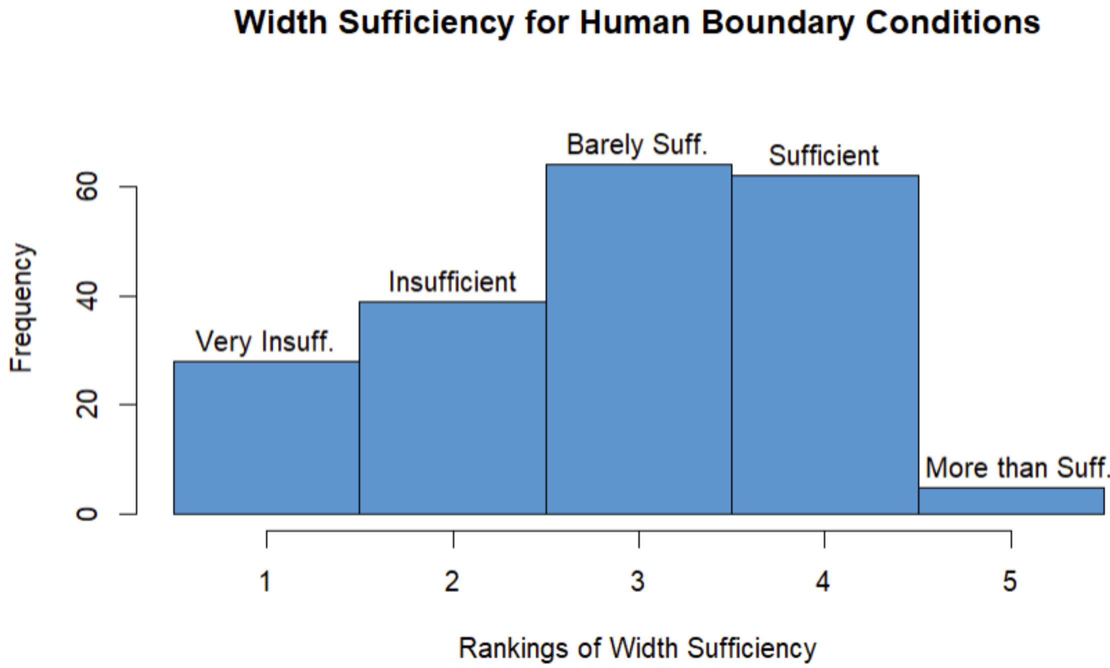

Figure 4.14: Sufficiency rating of seat width in human boundary conditions of all boundary widths

both Insufficient and Sufficient (an overall "middle ground" response). Comparing the real human condition and the one-sided physical barrier yields similar results, showing an insignificant rating in the space sufficiency between the two scenarios.

A conclusion can thus be drawn that people are very rarely experiencing high levels of space or width acceptability or sufficiency when seated next to another passenger based on the more "neutral" responses. Few participants, however, said they had a Very Insufficient or Very Unacceptable amount of space. This could be, in part, due to the brief length of each trial and lack of passenger interaction.

Regarding the case of space sufficiency shown in Figure 4.16, the most commonly reported rating was Barely Sufficient; this may be related to the amount of personal space they felt they had when seated next to a research assistant. In contrast to the histograms for the physical boundary conditions which feature the highest frequency reporting of Very Unacceptable/Very Insufficient, the histograms for a human boundary condition indicate more overall acceptability and sufficiency. However, true parallels cannot be drawn between the two as a result of the two-sided nature of the physical boundary conditions and the one-sided nature of the human boundary condition trials.

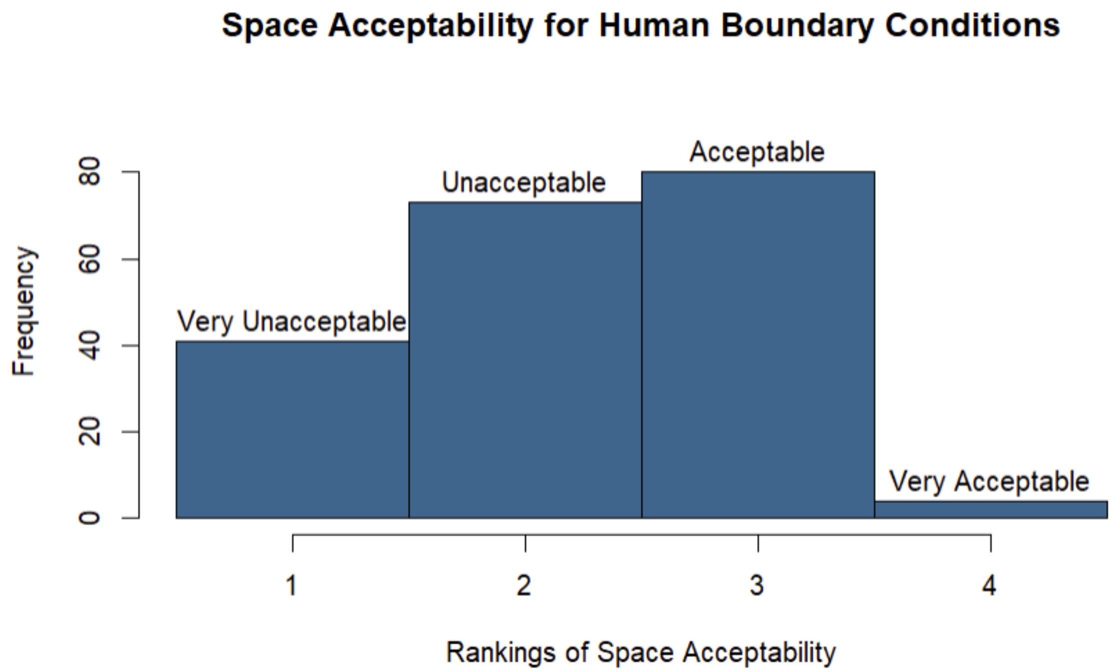

Figure 4.15: Acceptability rating of space in human boundary conditions of all boundary widths

4.2.4 Acceptability and Sufficiency when Bideltoid Breadth Equals Seat Width

After examining different interactions between conditions and reported sufficiency and acceptability of width and space, a relationship between bideltoid breadth and boundary condition width should be considered. Out of the 50 participants with 35 trials each, 59 total cases in which bideltoid breadth *equals* boundary condition width took place. The trials examined in this section were regrouped based on this specific bideltoid breadth interaction. The purpose of using bideltoid breadth as the boundary condition width is to determine if accommodation increases when using bideltoid breadth as a design metric rather than seated hip breadth. The cases for acceptability and sufficiency of both width and space where bideltoid breadth equals the boundary width is shown in Figures 4.17 - 4.20.

Examining the histogram for the acceptability of width (Figure 4.17), the distribution leans toward being Acceptable/Very Acceptable on the response scale, meaning participants viewed the boundary width that was as wide as their bideltoid breadth with satisfaction the most frequently. Comparatively, as shown in Figure 4.13, the two-boundary condition response for width

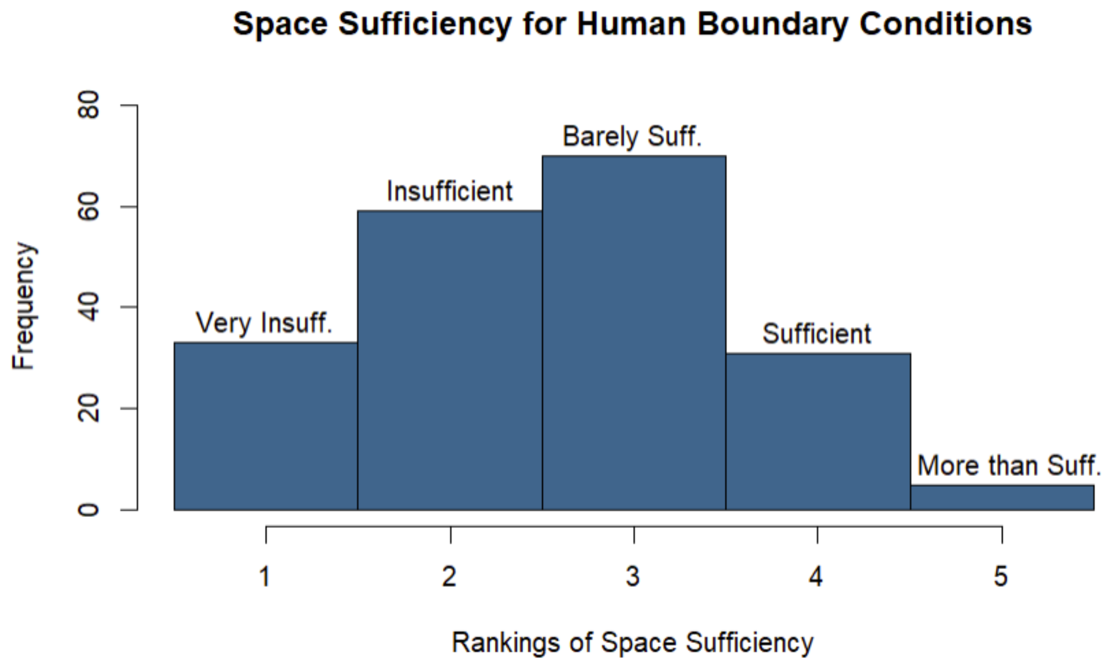

Figure 4.16: Sufficiency rating of space in human boundary conditions of all boundary widths

acceptability has a more vague distribution, but a large portion is considered to be Very Unacceptable/Unacceptable.

Looking at the width sufficiency case in Figure 4.18, the trend again shows more distribution toward the higher ratings of Sufficient and More than Sufficient and very few cases in the lower range (Very Insufficient/Insufficient). This figure and the histogram for width acceptability corroborate with one another by illustrating how a seat width equalling bideltoid breadth leads to a more acceptable and sufficient width.

The amount of space in terms of acceptability is shown in Figure 4.19. Following a similar trend to the width sufficiency and acceptability histograms, the distribution trends slightly toward the right, where a slight majority of responses were Acceptable. However, just short of the same number of responses was Unacceptable, meaning that a strong claim cannot be made whether or not a seat width being the same as bideltoid breadth provides acceptable space. Observing the figure, a claim can be made based on responses that a participant is unlikely to experience either a Very Unacceptable or Very Acceptable response. In regards to space sufficiency, a participant will either perceive their amount of space as a“moderate” rating of Acceptable or Unacceptable,

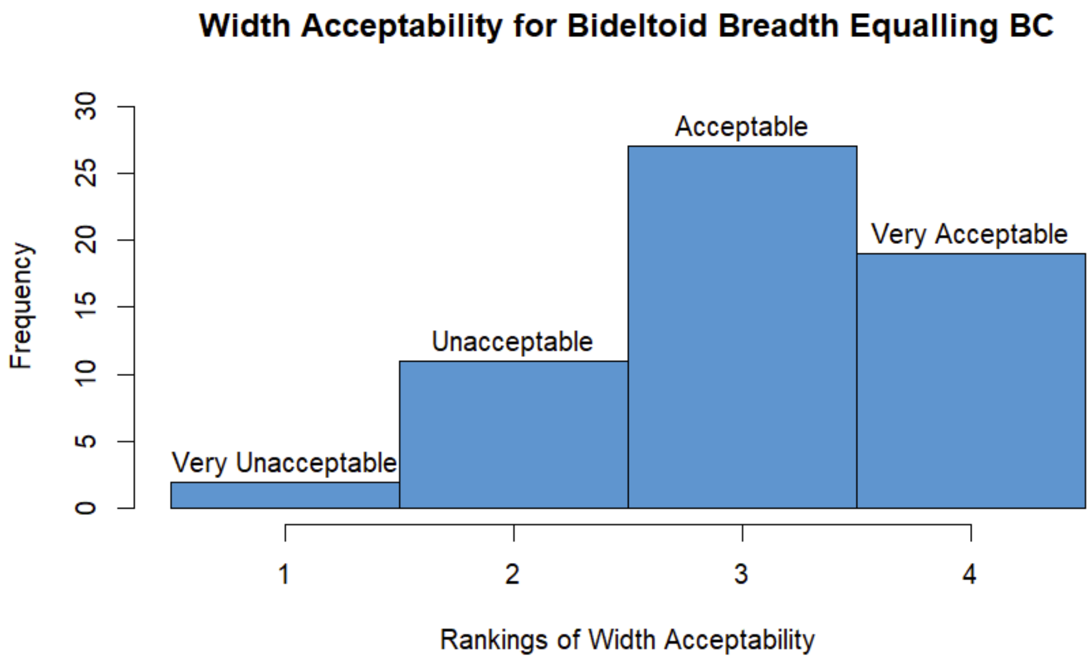

Figure 4.17: Acceptability rating of seat width when bideltoid breadth equals the boundary condition width

but will not have an extreme response.

In terms of space sufficiency for bideltoid breadth equalling the seat width, the distribution is shown in Figure 4.20. As is the case in Figure 4.17, Figure 4.18, and Figure 4.19, the distribution trends to the right, with the most frequently reported response being Sufficient and the next most frequently reported being Barely Sufficient. The few responses at Very Insufficient, Insufficient, and More than Sufficient indicate a similar, neutral response to the amount of space in this scenario. Compared to the width acceptability and sufficiency, the responses for the space acceptability and sufficiency fall short of trending toward Very Acceptable or More than Sufficient, however, participant replies indicate a satisfactory amount of space.

4.2.5 Overall Comfort

For each specific case (bideltoid breadth > seat width, any bideltoid breadth with a human condition, one-sided boundary, and bideltoid breadth = seat width), different correlations have been established in terms of comfort and acceptability. In general, participants were satisfied

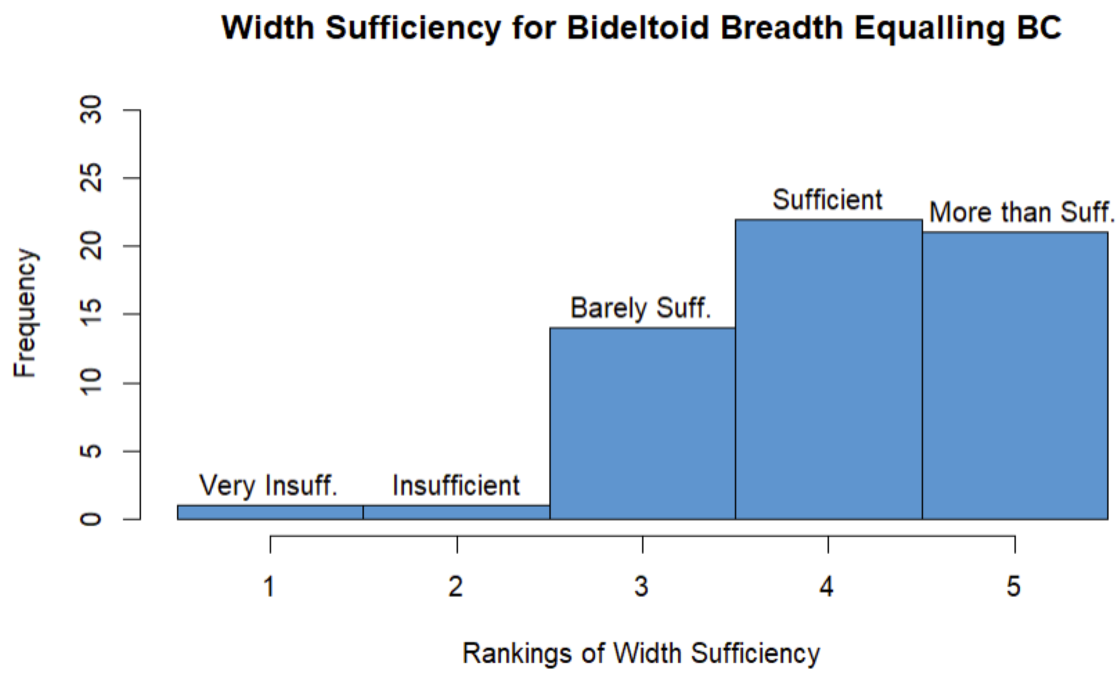

Figure 4.18: Sufficiency rating of seat width when bideltoid breadth equals the boundary condition width

when their bideltoid breadth was the same as the seat width, were not as satisfied when bideltoid breadth exceeded the seat width in both space and width, and were fairly satisfied when seated next to another passenger in general. A histogram is shown in Figure 4.21 to illustrate not only the overall accommodation based on comfort levels ranging from 1-100 (x-axis), but the different accommodation averages of the scenarios listed above.

As shown in Figure 4.21, the average comfort rating for the bideltoid breadth exceeding the seat width is 21.9, the lowest rating by a large margin as pictured on the plot. This case not only features a seat width that is narrower than an individual's bideltoid breadth, but also features a dual-boundary condition scenario, further enhancing levels of a passenger feeling uncomfortable. The reason behind the examination of a two-boundary condition was to establish a physical scenario on what is known about passenger comfort in relation to airplanes; the higher the load factor in an airplane, the more densely packed it will be, meaning that passengers are more likely to sit next to other passengers. As a result, they will experience higher levels of stress and lower overall levels of well-being through this encroachment on their personal space. Not only will there be

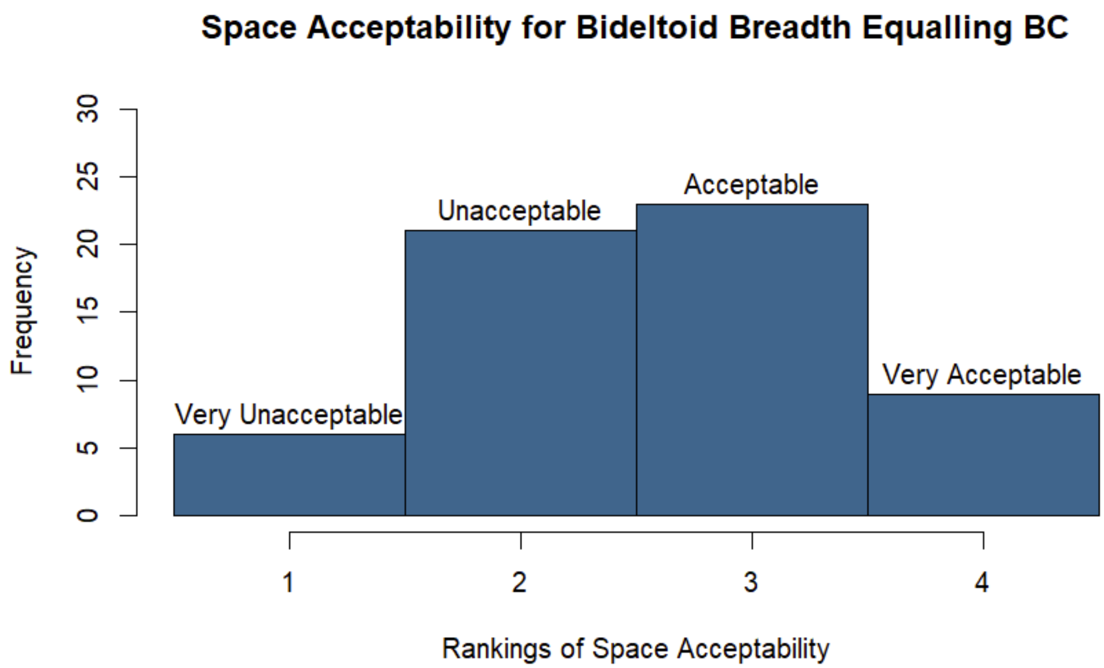

Figure 4.19: Acceptability rating of space in human boundary conditions when bideltoid breadth equals the boundary condition width

interpersonal interactions with other passengers, passengers will experience a *physical* interaction; in this scenario, the seat width was limited to being narrower than someone's bideltoid breadth. As a result, the experimental design guaranteed bideltoid breadth interaction, creating even further encroachment on personal space. Airline design decisions may increase their own profit through decreased seat size and increased load factor, but shrinking a seat creates more issues than it solves.

In the case of the one-sided boundary condition, the average comfort level was a 41.7; based on the responses of two-sided versus one-sided boundary conditions, it could be seen that lower levels of sufficiency and acceptability occurred in the case of two-boundary conditions. As a result of the increased comfort rating of a one-sided boundary condition, it can be implied that a higher comfort rating means higher levels of both sufficiency and acceptability for width and space. In terms of airline design, the interaction between two adjacent passengers rather than three, especially when someone is in the middle seat, is shown to create more passenger satisfaction; the consideration of passenger interaction in airlines could indicate the potential altering the seating layout in airplanes.

Regarding the human boundary condition where seat width was not a limiting factor, an average

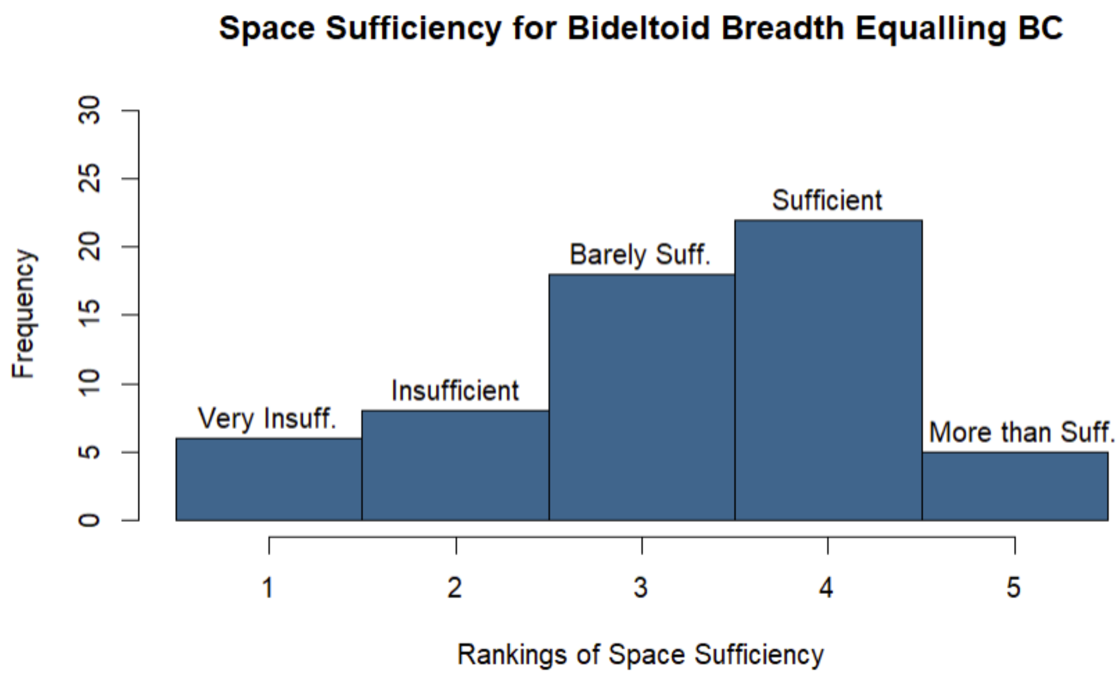

Figure 4.20: Sufficiency rating of space in human boundary conditions when bideltoid breadth equals the boundary condition width

comfort level was reported as 38. This ranking falls between the overall reported accommodation of the two-sided and one-sided boundary condition, implying that although better than a dual-boundary condition where the seat width is narrower than bideltoid breadth, is not as comfortable as the case of a single boundary condition. The purpose of gathering both physical boundary data and human boundary data was to compare the two, gaining insight into how participant's perception of personal space was altered with a real personal next to them (representing a real airplane scenario).

The mean overall accommodation value for all trials (every boundary condition and every seat width included) fell at 44.3, and in the case where boundary condition and seat width were the same, the average comfort level was at 45.9. The overall rating falls lower than that of the condition with bideltoid breadth equalling seat width, potentially impacting future airline design. Rather than designing around the seated hip breadth of a population, which is smaller for nearly all individuals compared to their bideltoid breadth, designers may consider using bideltoid breadth as a design metric when it comes to adjacent seating. Airline design is inherently different than the

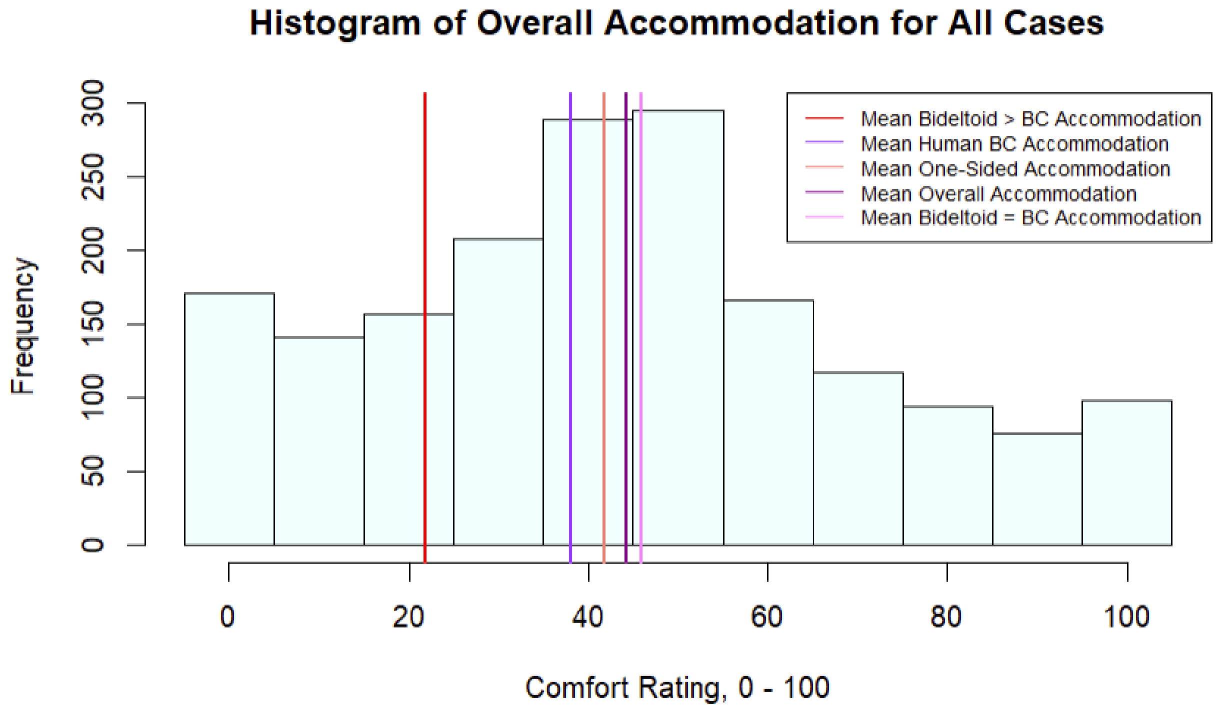

Figure 4.21: Histogram of all cases listed above: bideltoid breadth exceeding seat width (two-sided), human boundary condition (one-sided), one-sided physical boundary, bideltoid breadth equalling seat width (all seat widths and cases), and overall experimental accommodation

ANSI/HFES 100-2007 office seating standard, which does not have any interaction as airline seating. With the comfort level for a seat width narrower than bideltoid breadth doubling in rating after increasing to equalling a passenger's bideltoid breadth, it becomes apparent that bideltoid breadth as a key focal point provides both better accommodation and higher levels of comfort for passengers.

Based on the ANSUR II military data, to accommodate 90% of the population (including both males and females) should be at 544 millimeters. Compared to the current standard of 432 millimeters for seat width, this difference may not be realistic to implement given airline desire for increased profit. However, a middle-ground approach may be reached in order to not only successfully accommodate more passengers, but to increase their comfort when travelling by air.

Chapter 5

Discussion

This concluding chapter discusses the results of the study within the scope of airplane seat design, highlighting the importance of the work presented in this thesis. In addition, the limitations of the study are presented, noting key points that may have impacted the study and that should be kept in mind when considering the results. Finally, future work in the field of designing for human variability is discussed through the lens of both limitations of the study and design in human-occupied spaces.

5.1 Implications on Airplane Seat Design

As a result of the statistical analyses provided in Chapter 4, several takeaways can ensue. Firstly, the differences in rankings between the two-sided and one-sided boundary conditions imply that there is less acceptability and sufficiency overall when a two-sided boundary condition occurs. The issue of increased load factor in modern airlines directly ties to this claim; if an airplane has more passengers packed in, the more likely a passenger is to sit next to someone else, decreasing their overall satisfaction of the scenario and a resultant lower comfort level. Additionally, based on the general results from reported values of sufficiency and acceptability, a conclusion can be drawn that higher sufficiency and acceptability rankings indicate a higher level of comfort. Finally, the highest average comfort rating belonging to the case where bideltoid breadth equals the seat width indicates a key focal point for future work in modern airlines to increase space and width accommodation and sufficiency, but passenger comfort and accommodation as a whole.

5.2 Limitations

Certain limitations occurred during this study as a result of the participant pool, experimental design, and other factors. One such limitation is the racial and ethnic diversity of the participant pool. Given that Pennsylvania State University is a diverse, but predominantly white campus, some lack of diversity should be mentioned in the scope of the experiment. For anonymity purposes, racial and ethnic backgrounds were not recorded, so a racial and ethnic breakdown is not available. Although race and ethnicity factors were not taken into account in this experiment, they are not predictors of body size and shape; those differences are due to anthropometric differences between the sexes. Therefore, although race and ethnicity factors may have affected user preference in some way, there was no impact on body size and shape.

The age range of participants had some variation, but largely consisted of younger adults with some scattered adult participants. With a mean age of 23.6 years old, the data lean toward a generally younger population due to the nature of conducting the experiment on a college campus. However, the body size and shape of the participants are anthropometric differences between sexes rather than age-predicted; there may be some age-related differences in user preference, however. Also related to preference is the amount of times someone typically flies in a year; one participant noted how unbothered they were during some of the typically more uncomfortable trials due to being a frequent flier. User preference is an important factor that impacts comfort and acceptability between participants.

Another important limitation also lies within the sample size; due to the difficulty of finding certain participants, certain bins were left incomplete or completely untouched. All of the bins were touched except for Bin C for men and Bin L for women. Both bins were for short individuals (<66 inches for men and <60.5 inches for women) with a BMI of >35. Ideally, these bins would have been filled, but due to the difficulty of finding those individuals, they were left unfilled. Additionally, some bins were over-sampled for the sake of gathering more data, but this could have created a skew in the data toward one population size. However, a plethora of robust data was still gathered from a sizeable population of varied individuals.

The research team also operated under the assumption that although our sample population was small, it acted as a true representation of the larger population which we sought out to make design recommendations for. However, this is just an assumption; the population sampled certainly provided valuable data, yet should not be overstated when it comes to designing for a real-world population more diverse in age, body size, and race and ethic factors.

Within the results section of human boundary conditions, few participants, ranked the width of their amount of space as Very Insufficient or Very Unacceptable, although human boundary results were not as acceptable or sufficient as the physical one-sided conditions. This ranking may come as a result of a multitude of factors. For example, a real life airplane passenger scenario features an extended time period sitting next to someone who may infringe on personal space more so than the research assistants did. As a result of the length of the trial, a participant may not have responded in the same way as a real airplane seating scenario. Additionally, some participants were friends or acquaintances of the research assistants, which may have led to higher levels of acceptability or sufficiency based on the familiarity aspect.

Although a majority of the experiments were completed with the same set of male and female individuals for the human boundary conditions, differences occurred for some trials; after the graduation of the initial male (Luke), a different male was implemented into the trials. Additionally, due to a schedule conflict due to one of the final weeks of data collection, the initial female (Riley) was replaced by another female for a total of four trials as a result of the time constraint for this thesis and thus, the experimental timeline. Though the differences may not be statistically significant, there would have certainly been some variation in human boundary condition results due to personal preference of a participant.

In addition, the testing procedure is different than that of ANSUR I and ANSUR II data, where participants wore minimal clothing (male participants wore nylon shorts and women wore the same short with the addition of a bra) to get the most anthropometrically accurate measurements possible [13]. During the airplane experiment testing procedure in the OPEN Design Lab, the same attire was not used; participants were told to remove their shoes for an accurate stature measurement, however, there were limitations on other measurements. Participants were told to take off their coats or sweatshirts to aid in bideltoid breadth measurements, but when it came to the seated hip breadth measurement, the variation in pants (jeans, sweatpants, leggings, etc.) must be taken into account. Research assistants controlled ensured all participants took any items out of their pockets, but with no streamlined pair of form-fitting pants for every user, the difference must be taken into account.

5.3 Future Work

In future iterations of this study, a wider range of participants may be studied, not only in number, but in age. Although the diversity was not entirely one-dimensional, future versions of studies for human-occupied spaces may consider seeking out participants in older age groups to gather more variation in body size. Additionally, from a data perspective, the volume of participants studied in a study such as the Army personnel study ANSUR or in the National Health and Nutrition Examination Survey (NHANES) are more rich in data than a smaller-scale study like this one. However, given the time constraints of the study, for the purpose of this thesis, the data gathered is sufficient to determine trends and draw conclusions.

Expanding beyond this particular study and into the field of human-centered, considerate design, a multivariate approach is essential to achieve true accommodation. When it comes to human-occupied spaces, the relationship (or lack thereof) between different anthropometric measurements should be taken into account for successful design. Furthermore, the lifetime of a product should be considered in design; if the body mass index (BMI) of a population is increasing over the years, the seat of an airline seat should not be shrinking year after year. Additionally, the adjustability and sizing of a product could be considered–in the realm of airline seating, perhaps the solution may be different seat sizes available for people with larger body size to better accommodate those individuals.

In order to create considerate designs that can successfully accommodate generations of people, thoughtful design approaches must be implemented to truly design for human variability.

Bibliography

[1] E. L. Miller, S. M. Lapp, and M. B. Parkinson, "The effects of seat width, load factor, and passenger demographics on airline passenger accommodation," *Ergonomics*, vol. 62, pp. 330–341, 2 2019.

[2] Center for Disease Control, "Adult obesity facts," https://www.cdc.gov/obesity/data/adult.html#print, 2022, accessed: (2023-04-05).

[3] K. H. Kroemer, "Engineering anthropometry: Federal institute of occupational safety and accident research," *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 20, 7 1976.

[4] Federal Aviation Administration, "Federal airline administration aerospace forecast," *United States Department of Transportation*, 1 2017.

[5] L. Zhang, "Identifying factors of comfort and discomfort in sitting," *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 38, pp. 377–389, 1996.

[6] L. Lewis, H. Patel, M. D'Cruz, and S. Cobb, "What makes a space invader? passenger perceptions of personal space invasion in aircraft travel," *Ergonomics*, vol. 60, pp. 1461–1470, 11 2017.

[7] G. W. Evans and R. E. Wener, "Crowding and personal space invasion on the train: Please don't make me sit in the middle," *Journal of Environmental Psychology*, vol. 27, pp. 90–94, 2007.

[8] P. Vink, C. Bazley, I. Kamp, and M. Blok, "Possibilities to improve the aircraft interior comfort experience," *Applied Ergonomics*, vol. 43, pp. 354–359, 3 2012.

[9] F. Kremser, F. Guenzkofer, C. Sedlmeier, O. Sabbah, and K. Bengler, "Aircraft seating comfort: The influence of seat pitch on passengers' well-being," *Work*, vol. 41, pp. 4936–4942, 2012.

[10] C. de Vries and M. B. Parkinson, "Limiting disproportionate disaccommodation in design for human variability," *Ergonomics*, vol. 57, pp. 52–65, 1 2014.

[11] K. Case, M. Porter, R. Marshall, and R. Oliver, "Virtual fitting trials in 'design for all'," in *'Building on Manufacturing Advances of the Nineties', Proceedings of the Seventeenth Annual Conference of the Irish Manufacturing Committee*, 8 2000.

[12] C. Gordon, T. Churchill, C. Clauser, B. Bradtmiller, J. McConville, I. Tebbetts, and R. Walker, "Anthropometric survey of u.s. army personnel: Summary statistics, interim report for 1988," U.S. Army Natick Soldier Research, Development and Engineering Center, Tech. Rep., 1989.

[13] C. Gordon, "U.s. army anthropometric survey database: Downsizing, demographic change, and validity of the 1988 data in 1996," U.S. Army Solider Systems Command Natick Research, Development and Engineering Center, Tech. Rep., 10 1996.

[14] National Center for Health Statistics, "Vital and health statistics series 2, number 184 april 2020: Sample design and estimation procedures data evaluation and methods research," 2015. [Online]. Available: https://www.cdc.gov/nchs/products/index.htm.

[15] Anthrotech, "Debunking myths about male and female bodies," https://anthrotech.net/2017/10/13/debunking-myths-about-male-and-female-bodies/, 10 2017, accessed: (2023-03-21).

[16] K. Robinette, T. Churchill, and J. McConville, "A comparison of male and female body sizes and proportions," *Aerospace Medical Research Library*, 7 1979.

[17] C. C. Perez, *Invisible Women: Data Bias in a World Designed for Men*, P. Hampson and J. Stoltz, Eds. Abrams, 2019.

[18] J. Molenbroek, "The average man does not exist," *International Journal of Environmental Research and Public Health*, 2 2022.

[19] C. Devries, G. Roach, and M. Parkinson, "A comparison of design for human variability strategies in seating requirements of anthropometrically diverse populations," *International Conference on Engineering Design*, vol. 5 DS75-05, 2013.

[20] World Data, "Average height and weight by country," https://www.worlddata.info/average-bodyheight.php, 2020, accessed: (2023-03-21).

[21] R. A. Walker, "The impact of racial variation on human engineering design criteria," *National Association for the Practice of Anthropology Bulletin*, vol. 13, pp. 7–21, 1 2008.

[22] H. Martin, "Airline seats have been getting smaller for years. is the shrinking coming to an end?" *Los Angeles Times*, 8 2022.

[23] Z. Jianghong and T. Long, "An evaluation of comfort of a bus seat," *Applied Ergonomics*, vol. 25, pp. 386–392, 1994.

[24] Center for Disease Control, "Defining adult overweight & obesity," https://www.cdc.gov/obesity/basics/adult-defining.html, 2022, accessed: (2024-4-02).

[25] HFES 100 Committee, "Ansi/hfes 100-2007 human factors engineering of computer workstations," Human Factors and Ergonomics Society, Tech. Rep., 2007.