Thirty years of anthropometric changes relevant to the width and depth of transportation seating spaces, present and future

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ABSTRACT

This paper reports the results of an investigation into changes in body shape anthropometry over the past several decades and discusses the impact of those changes on seating in transport, especially airliners. Changes in some body shape dimensions were confirmed in a sample of students at TU Delft; several of the changes, e.g. hip breadth, seated, are relevant to the ongoing design of seating. No change in buttock knee length was observed.

The fit between current user anthropometry and current airline seat design, especially regarding seat width, was investigated. A comparison of the average current seat breadth with global anthropometric data suggests that accommodation may be problematic, with less than optimal width for passengers' shoulder and elbow widths.

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1. Introduction

1.1. Changing anthropometry and seat size accommodation

This paper investigates anthropometric information relevant to the design of seating in transportation, especially for air transport. It first considers whether anthropometric data relevant to the design of seating are changing. It then looks at the current state of anthropometric accommodation in international economy-class airline seating.

It is well-established that humans' width and circumference measurements have been increasing at a greater rate than have heights for several decades. This can be seen in increases of body mass relative to height. The Body Mass Index (BMI) is defined as an individual's body mass in kilograms divided by the square of his or her height in meters. Finucane et al. (2011), in a study with more than 9 million participants, found that the average BMI of males worldwide has increased by 0.4 kg/m^2 per decade and that the average BMI of females has increased by 0.5 kg/m^2 per decade since 1980. Further details regarding the secular trend towards an increase in body dimensions relevant to the design of seating are presented in section 2 of this paper.

Consequently, updated anthropometry continues to be both relevant and necessary for the design of transport seating. Buttock to knee length, hip breadth seated, forearm to forearm breadth, and shoulder breadth are important dimensions for design of the distance between two seats and seat width, respectively, in aircraft, buses and trains (Roebuck et al., 1975). For passengers' comfort, aircraft seat design (Smulders et al., 2016) and seat widths and depths are identified as an important factor regarding passengers' perception of comfort (Ahmadpour et al., 2014). Seat widths may be subject to economic constraints to increase the number of seats within any given fuselage (Ahmadpour et al., 2014). However, this paper argues that the width of those seat designs should be expected to accommodate a reasonable proportion of the people sitting in them, especially for seating in long-duration flights.

1.2. Relevance of anthropometry to the design of the passenger seating space volume

This paper reemphasizes the concept of the seating space volume, defined by the width, length and seated height of passengers (Roebuck et al., 1975, Quigley et al., 2001). The desired dimensions of the seating space volume are those that concurrently accommodate a given proportion of all passengers on all three dimensions. However, only two of the three relevant dimensions of

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the seat space volume, width and depth, are discussed in detail in this paper while the height of the space is not.

One might arbitrarily define the dimensions of the seating space volume as the 95th percentile values of sitting widths, lengths and heights of the individuals who use various modes of transportation, especially airline seats (Quigley et al., 2001). It is important to note that, although 95th percentile values are used to define the space in this paper, this does not necessarily ensure exactly 95 percent accommodation. The method of estimating the accommodation achieved by combining these three 95th percentile dimensions (or indeed, of combining any percentile dimensions) is more completely described in Albin and Molenbroek (Albin and Molenbroek, 2016) and in section 4.3.1 of this paper.

1.2.1. Seating volume height

The height of the seating space is determined in this paper by the 95th percentile value of sitting height above the floor. Generally, this dimension is not directly measured and might be estimated by adding the 95th percentile values of popliteal height and sitting height. Although methods of interpreting the accommodation achieved by combining two percentile values has recently been described (Albin, 2017), this paper does not deal with the height of the seating space.

1.2.2. Seat pitch

Seat pitch is the horizontal distance between a point on a seat and the same point on the seat directly ahead of or behind it, for example, the distance between the front edges of two tandem seats (where one is behind the other).

The anthropometric dimension, buttock knee length, is relevant to establishing the seat pitch dimension in aircraft, buses and trains. If the horizontal thickness of the seat backrest at the level of the buttocks is added to the measurement of the buttock knee length, then the minimum seat pitch dimension while sitting can be calculated (Vink and Brauer, 2011). It must be emphasized that this should be considered as the minimum seat pitch dimension, as it does not allow space for movement; some additional depth should be added to afford clearances for garments and postural change and to enable entering and exiting the seat (Quigley et al., 2001). The longest buttock knee length reported in the ISO 7250-2 Technical Report is that of Dutch males, whose 95th percentile value for buttock knee length is 703 mm. Any changes in that anthropometry, such as a trend towards increasing buttock knee length, would imply that seat pitch would also need to increase to provide sufficient accommodation.

1.2.3. Seating space width

The width of the seating space varies with its height above the floor; in this paper, it has the width of the 95th percentile hip breadth seated value, female at the level of the seat surface; the 95th percentile elbow to elbow breadth, male at the level of the armrest, and the 95th percentile bideltoid shoulder width, male at the level of the shoulders. Clearly, hip breadth seated, bideltoid shoulder breadth and elbow to elbow breadth are relevant for the design of the width of bus, train and aircraft seats (Roebuck et al., 1975).

However, reducing seat width opens the possibility of seating more passengers next to each other (side by side) in the vehicle. For example, the basic seat plan for the Boeing 787 was a 2-4-2 (8 seats across) configuration. Except for Japan Air Lines and All Nippon Airways, most airlines chose a 3-3-3 (9 seats) configuration, which narrowed seat width to less than 457 mm (18 in) (Vink and Brauer, 2011). However, a narrower seat may not accommodate the hip breadth, seated, the elbow to elbow breadth or the shoulder width of a significant fraction of the intended users.

A convenience sample of 508 airline seat widths for 84 international airlines and various aircraft has been reported by Seatguru (Seatguru, 2016). The Seatguru seat pitch and seat width measurements (distance between the armrests) were reported to Seatguru by travellers and/or by the airlines (Carter, 2017). If more than one seat width or seat pitch value was given by Seatguru for an airline's aircraft, the minimum value was used to compute the overall average. The average and (standard deviation) of seat width on economy long-haul flights was 447.4 (15.5) mm and the average seat pitch was 816.0 (37.9) mm, or 17.6 (0.6) inches and 32.1 (1.5) inches for seat width and seat pitch, respectively. Although the Seatguru data are a sample of convenience, the average seat width between armrests reported in Seatguru is consistent with the average airliner seat width range of 430 mm–470 mm reported earlier by Ahmadpour et al. (2014) and an average airliner seat width of 436 mm reported by Goonetillike and Feizhou, (Goonetilleke and Feizhou, 2001).

The width of the seating space volume is partially determined by elbow to elbow breadth and/or shoulder breadth; these widths are critical in assessing the accommodation achieved by seat width design when people are seated side-by-side (Roebuck et al., 1975). Humans, particularly males, are somewhat wedge-shaped, and are wider at the shoulders and elbows than at the hips.

The anthropometric data in ISO 7250-2 (ISO, 2010) show that males' average shoulder breadth is 103 mm wider than their seated hip breadth and that females' shoulder breadth is 44 mm greater than their seated hip breadth.

This is a critical issue, as there may be insufficient space to accommodate passengers' shoulders in side-by-side seating, leading to concerns for passenger health and comfort. In such cases, the shoulders and elbows of a large passenger may overlap the seat boundaries into the seating space of the adjacent passengers. Changes in these width measurements would necessarily affect the anthropometric accommodation of transport seating.

The perception of intrusions or invasions into one's personal space are relevant to the design of seating (Li and Hensher, 2013). Evans and Winter (Evans and Wener, 2007) noted that this effect is so strong that many train passengers preferred to stand rather than sit in an open middle seat. They hypothesized that placing seats in pairs rather than three or more across might be preferable regarding a sense of maintaining inviolate one's perception of personal space. Vink et al. (2012) note that there are "clear relationships between comfort and legroom, hygiene, crew attention and seat/personal space" in aircraft. Gender may play an interesting role in the perception of personal space. For example, Fisher and Byrne (Fisher and Byrne, 1975) noted that females are more likely than males to perceive adjacent overlap as an intrusion into their personal space, while males are more sensitive to face-to-face intrusions. While the perception of personal space is an interesting and relevant topic in seating design, this paper only discusses anthropometric accommodation.

There are additional clearance dimensions of interest within the seating space volume. As examples, thigh height is important in defining the tray table height with respect to the seat pan height and elbow rest height relative to the seat pan is important in determining arm support heights. For seat pan height, the popliteal height is of interest and for seat pan length the buttock-popliteal length is relevant. Seated height above the floor defines the height of the seat space volume. These and other important seating dimensions, such as the height of the seat above the floor, allowances for tilted seat backs, tray tables, armrests, etc. are contained within the seating space. However, those dimensions are not discussed in detail in this paper, which focuses on the anthropometric dimensions that describe the length and width of the seating space volume.

A schematic drawing of the seating space is shown in Fig. 1.

Sources of anthropometric data, such as tables of percentiles of anthropometric information for various nationalities, cultures and age groups are common (ISO, 2010, Molenbroek, 2004, Pheasant, 1986, Harrison and Robinette, 2002, Roebuck, 1995, Peebles and Norris, 1998, Norris et al., 1999, Steenbekkers et al., 1999). However, as previously mentioned, there are strong indications that anthropometric data are, at least in part, changing. That change is most apparent in the "fleshy" dimensions (Finucane et al., 2011).

2. Secular trends in anthropometric measurements

These trends in changing anthropometrics are usually described with a few measures such as stature and weight. Secular trends toward increases in both are seen in some developing countries such as China (Ji and Chen, 2008). Cole (Cole, 2003) suggests that stature is generally stable from about 1990 to the present in countries with developed economies, but that there is an ongoing increase in weight due to obesity. Similar trends to those suggested by Cole are observable in the United States military (McConville et al., 1972, Churchill et al., 1977, Gordon et al., 1989, 2014) and in the National Health and Nutrition Examination Survey (NHANES) anthropometric measures of civilians in the United States (McDowell et al., 2009, Fryar et al., 2012).

Clearly, a trend of increasing mass relative to height of individuals worldwide will impact the design of seat dimensions, especially for seats intended to continue to be used for many years, as it translates into greater seat width requirements at both the seating surface and at the level of the elbows and shoulders.

Seat pitch is determined largely by buttock to knee length. A trend towards increasing buttock knee length would imply that seat pitch dimensions would need to increase as well. Males from the Netherlands have the longest buttock knee length in the data ISO 7250-2 data. Schönbeck and her colleagues have shown that the height of Dutch males has been stable and has not increased since 1997 (Schönbeck et al., 2012). Consequently, if Dutch males' buttock knee length is confirmed to be stable, it would suggest that component of seat pitch dimensions to be stable as well.

2.1. Objective

The first objective of this paper is to determine whether these changes in anthropometrics are to be found in various populations, and if so, for which dimensions are the changes occurring? Secondly, it will assess the level of accommodation achieved by current aircraft seating design, and, finally, how might changes in anthropometric dimensions related to seating affect the dimensions required to achieve the desired level of accommodation?

2.2. Confirming changes in dimensions relevant to seat space design

Seated hip breadth was previously noted as a critical factor in the design of seating. Generally, females have greater hip breadths than do males. Hip breadth data are available for females in the US military in surveys performed in 1968, 1988, and 2012 (McConville et al., 1972, Churchill et al., 1977, Gordon et al., 1989, 2014). For those surveys, the average and (standard deviation) of hip breadths are 350.7 (22.5) mm, 384.5 (27.25), and 399 (32.7) mm in 1968, 1988 and 2012, respectively. Stature measures for those same three surveys were 1621 (60.0), 1629 (63.6) and 1628.5 (64.2) mm for 1968, 1988 and 2012. While the average stature measurements remained relatively constant, seated hip breadth increased markedly at a rate of about 3 percent per decade.

3. A unique opportunity to study anthropometric change over time in a Dutch population

Molenbroek et al. (Molenbroek et al., 2016) studied changes in anthropometric measures in the Netherlands during the last 30 years, comparing two samples drawn from the same population, industrial design engineering students at the Delft University of Technology. A survey completed in 1986 (Molenbroek, 1994) was compared to a new measurement of student anthropometry completed in 2014. Both surveys were completed using the same methodology (Molenbroek et al., 2016, Molenbroek, 1994). Although these data are based on a student population, they are the only data available with which to infer changes, or lack of changes, for the general population of the Netherlands for all the dimensions of interest relevant to seating design. As such, these data offer valuable insight into the stability or change in anthropometric measures in the Netherlands. Although Schönbeck et al. have suggested that Dutch males' and females' heights have been stable since 1997, they do not discuss other anthropometric dimensions relevant to seating, and it is especially of interest to be able to assess

A. Sitting height
B. Elbow height
C. Seat height
D. Thigh height
E. Buttock-knee length
F. Shoulder breadth
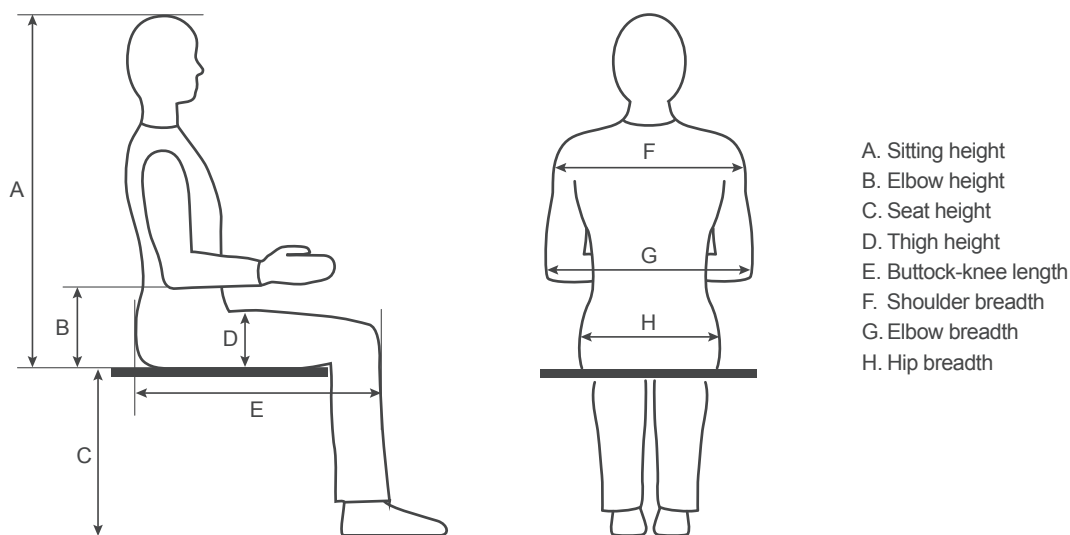G. Elbow breadth
H. Hip breadth

Fig. 1. Schematic drawing of some anthropometric dimensions relevant to the design of transportation seating systems.

the stability or lack of stability in Dutch males' buttock knee length to inform decisions regarding seat pitch dimensions (Schönbeck et al., 2012).

3.1. The research question

Which anthropometric measures relevant for the design of seat width and depth, if any, changed in 30 years between these two samples of the same comparable population?

3.2. Methods

The anthropometric measurements made of Delft University of Technology industrial design engineering students in 1986 were repeated in 2014. Measurements were gathered on about 350 students in each case. The students' ages varied from 18 to 25. Anthropometers were used to measure widths, lengths and depths of the body.

The sitting measurements were taken using a measuring chair like the one used by the Institute for Consumer Ergonomics (ICE) for the Institute for Consumer Ergonomics Seated Anthropometry Table (British Institute for Consumer ERGONOMICS, 1981). Each measurement was defined and measured according to the Netherlands Standardization Institute NEN-EN-ISO 7250-1 standard (NEN, 2010) to ensure that the correct measurement procedures were known and used. Additionally, some general data such as age, gender and weight were recorded. The measurements from 1986 to 2014 are compared in Table 1.

After the 2014 data collection was complete, t-tests were used to compare the mean values for the 1986 and 2014 anthropometric data for each measurement.

3.2.1. Ethics

Each participant was well informed and voluntarily participated in the collection of anthropometric data. An informed consent form that contained information about the purpose of the research, the anonymity of the obtained data, the tools and the method was signed by the individuals before participation. Participants were also advised they could quit at any time or deny any requests. The team conducting the experiment consisted of both men and women (master's degree students) so that individuals of the same sex as the participants could perform the measurements.

3.3. Results

Table 1 presents the anthropometric data of 1986 and 2014 for females and males. The means of five dimensions are statistically significantly different between the two surveys for both females and males. One of those dimensions is hip breadth. The males have on average a 15 mm (approximately 7%) wider hips and females on average a 26 mm (approximately 7%) wider hips.

Thigh height, the second dimension differing significantly for both males and females, was 3 mm more for males (approximately 5%) and 7 mm for females (approximately 5%).

Elbow height seated is the third dimension that is different between 1986 and 2014. For both females and males, the elbow height is 25 mm more (approximately 10% for both) in 2014 than in 1986.

The fourth value for which a significant change was observed is eye height, which was 11 mm and 12 mm greater for males and females respectively in 2014, a 1.5% difference.

The fifth significant change is in popliteal height sitting, which increased 3 mm and 2 mm for males and females respectively in 2014 than in 1986, which is about 1% and 0.5%, respectively.

Table 1
Number of observations, fifth percentile, ninety-fifth percentile, average and standard deviation for the dimensions measured in 1986 and 2014. P is the p value for the *t*-test on the differences between both populations and t is the t-value of this test. An asterisk * indicates statistical significance with P < 0.05.

	Male										p	t
	1986					2014						
	n	p5	p95	x	Sd	n	p5	p95	x	sd		
stature	265	1714	1930	1819	66	193	1714	1942	1821	71	0.757	0.310
breadth elbow-elbow(standing)	265	390	488	436	29	194	381	500	438	35	0.504	0.668
hip breadth seated*	265	320	384	348	19	194	328	404	363	23	0.000	7.638
shoulder breadth (deltoid)	265	426	490	457	21	194	416	494	457	24	1.000	0.000
thigh height*	265	123	158	139	10	193	121	166	142	13	0.006	2.791
buttock popliteal depth*	265	457	539	501	25	193	470	558	511	27	0.000	4.086
buttock-knee length	265	586	678	633	30	193	586	680	634	29	0.475	0.714
buttock-foot length	152	1012	1184	1102	52	193	1005	1192	1100	57	0.697	0.390
elbow height*	265	191	279	235	27	194	217	303	260	28	0.000	9.647
eye height seated*	265	779	881	827	33	193	780	899	840	35	0.000	4.056
popliteal height sitting	152	447	535	492	27	194	451	544	495	29	0.326	0.984
sitting height	263	899	1000	946	33	194	891	1010	949	35	0.350	0.936

	Female										p	t
	1986					2014						
	n	p5	p95	x	Sd	n	p5	p95	x	sd		
stature	89	1592	1790	1700	65	153	1598	1809	1698	63	0.814	0.235
breadth elbow-elbow (standing)	89	353	468	404	35	153	346	467	402	33	0.657	0.445
hip breadth seated*	89	316	404	354	26	153	342	434	382	27	0.000	7.885
shoulder breadth (deltoid)	89	380	456	413	21	153	387	453	418	21	0.075	1.786
thigh height*	89	117	164	140	14	153	128	171	147	14	0.000	3.751
buttock popliteal depth	87	445	548	488	31	153	449	536	495	25	0.058	1.908
buttock-knee length	89	561	650	602	30	153	544	640	600	28	0.602	0.522
buttock-foot length	88	958	1110	1031	50	153	943	1116	1031	50	1.000	0.000
elbow height*	89	188	277	233	25	153	221	309	259	25	0.000	7.801
eye height seated*	89	723	823	775	34	153	737	844	787	30	0.005	2.855
popliteal height sitting	85	415	481	449	24	153	406	491	451	27	0.570	0.569
sitting height*	89	838	942	889	31	153	847	951	898	31	0.035	2.127

In addition, females average sitting height increased by about 9 mm, or 1% between 1986 and 2014.

It is of interest to see that many measurement values relevant to seating space design remained constant with no statistically significant differences over thirty-year's time. Shoulder width had p value of 1 when comparing males of 1986 and 2014; buttock-foot length had a p value of 1 for females; and buttock-knee length had p values for females and males, respectively, of 0.6 and 0.7, indicating that little has changed in these values during the thirty-year interval.

3.4. Discussion

While these results reflect changes in a sample of convenience drawn from a very specific population, students of the faculty of Industrial Design Engineering in Delft, the increases that they show are consistent with the increases seen in other populations. In this student population, many anthropometric measures relevant for seat design changed over the 30-year interval. Hip breadth measurements for students increased at a rate of slightly more than 2 percent per decade, roughly equivalent to the 3 percent rate of increase per decade seen for US military females between 1968 and 2012.

Eye height above the seat and elbow height above the seat also increased significantly for both males and females.

Finally, males' buttock popliteal length increased significantly as did females' seated height. The increase in buttock popliteal length may impact future seat depth accommodation.

Although females' seated height appears to be increasing, they are likely to be accommodated by the corresponding male seat height dimensions, which are generally greater. But this introduces a secondary problem, sitting with the feet unsupported; such lack of foot support has long been identified as a source of seating discomfort. Recently, Mastrigt and Vink have noted that foot support is an important component of seating comfort for large segments of air travellers (Hiemstra-van Mastrigt, 2015).

It appears that there may be an age effect to consider as well. There are comparable (same measurement protocol) anthropometric data for the Netherlands from a survey performed during 1999–2000 for individuals aged 18–65 years, which are reported in ISO 7250-2. There the mean hip breadth (standard deviation) for males was 383.1 (29.8) mm and 418.9 (38.3) mm for females, much greater than those reported for the student sample. However, thigh clearance heights for the ISO sample averaged 146.2 (14.5) mm for males and 146.9 (14.6) mm for females; roughly comparable to the students' measurements.

3.4.1. Impact on changing anthropometry on design for seat width

It is important to note that the value of hip breadth, seated appears to be increasing for multiple populations, as is indicated by the student data gathered at TU Delft and the US military data, and that is appears to be increasing at a rate of about 2–3 percent per decade. To illustrate this, while a seat width of 404 mm (15.91 in.) would just accommodate 95 percent of females in 1986, the corresponding width in 2014 would have to be 434 mm (17.1 in), a 7.4 percent increase in width.

3.4.2. Impact of changing anthropometry on design for tray tables, armrests and video screens

A clearance space of 164 mm was just sufficient to allow TU Delft students' thighs to fit beneath a tray table in 1986. However, the requisite clearance increased to 171 mm in 2014.

Armrests should allow space between and under the armrest for thigh clearance. While an armrest height of 235 mm was just adequate to accommodate 95 percent of TU Delft students in 1986,

that dimension increased to 260 mm by 2014.

It may be important to consider use of alternate armrest forms, such as that promoted by Hiemstra-van Mastrigt (Hiemstra-van Mastrigt, 2015), who suggested that armrests have a triangular cross section in the sagittal plane. The triangular cross section provides a wide support surface for the arms, but increases clearance for the thighs. Additionally, it eliminates or reduces contact pressure between the edge of the armrest and the thighs.

There is a small, but statistically significant change in eye-height, which is relevant to the placement of video screens and entertainment systems.

However, the scope of this paper is generally limited to the width and depth of the seating space, reserving further discussion of the design of tray tables, armrests and video screens for future research.

3.4.3. No change in anthropometric data relevant to seat pitch design

There was no significant change in buttock knee length observed for male or female TU Delft students between 1986 and 2014.

4. Part 2 – present anthropometric accommodation of airline seats

4.1. The research question

What level of accommodation do current seating dimensions provide for males and females from around the world?

In the second part of this paper, the anthropometric accommodation for airline seating is estimated using a global sample of anthropometric data from Africa, Asia, Europe and North America, reported in ISO 7250-2 (ISO, 2010). A survey of more than 500 airline seat width and seat pitch dimensions based on 84 different airlines' international economy class cabins may be found on the Seatguru website (Seatguru, 2016). This sample of convenience reported the mean and standard deviation of seat width to be 447.4 (15.5) mm and the current average seat pitch to be 816.0 (37.9) mm, or 17.6 (0.6) inches and 32.1 (1.5) inches for seat width and seat pitch, respectively. If more than one seat width or seat pitch value was given for an airline, the minimum value was used to compute the average. Seat width was defined as the distance between armrests.

4.2. Seat pitch accommodation

Dutch males have the largest 95th percentile buttock knee length value in the ISO 7250-2 dataset, 703 mm (27.7 in). If a seat back thickness of 40 mm and a movement allowance of 5 mm are added to the greatest buttock knee length, the minimum average seat pitch would be 748 mm (29.4 in). This is 78 mm (3.1 in) less than the average seat pitch of 816 mm (32.1 in) reported in the Seatguru data. There appears to be adequate clearance between seats while seated to accommodate upper leg length.

A second consideration regarding seat pitch is the ease of entering or exiting the seat. Quigley et al. (2001) suggest that a clearance of 211 mm (8.3 in) between the front edge of the seat pan and the back of the seat ahead allows acceptable clearance for ingress and egress from the seat. The present study does not include a direct measure of that distance but it is possible to infer from the anthropometric data in ISO 7250-2 whether a seat pitch of 816 mm provides sufficient clearance to enter or leave the seat.

Assuming the maximum depth of a seat is equal to the largest 95th percentile buttock popliteal length (Kenyan males, 570 mm, 22.4 in) and that the thickness of the seat back cushion is 40 mm,

then the clearance between the front edge of the seat with the back of the seat ahead is 816 mm—610 mm, or 206 mm, 5 mm less than the optimal value suggested by Quigley et al.

This is a conservative estimate of the space available to enter or exit from the seat; seat depths are generally less than the full buttock popliteal length. Goonetillike and Feizhou (Goonetilleke and Feizhou, 2001) reported average airline seat depths of 467 mm and noted that general guidelines for seat depths ranged from 200 mm to 470 mm. A seat pitch of 816 mm and a seat depth of 470 mm combined with seat back cushion 40 mm thick would allow 306 mm (12 in) clearance between the front edge of the seat and the back of the seat ahead.

4.3. Seat width accommodation

The percent of males and females accommodated by a 447.4 mm seat space width was calculated for each national group reported in ISO 7250-2 (ISO, 2010) regarding hip, bideltoid shoulder and elbow-to-elbow breadths. In addition, the percent accommodated for each national group by the average seat pitch value of 816 mm was also estimated. The percent of males and females of seven different nationalities accommodated on each dimension results are shown in Table 2. Males are less likely to be accommodated on shoulder and elbow to elbow widths; females are less likely to be accommodated on hip breadth.

The values in Table 2 for the percent accommodated by a seat width of 447.4 mm was determined for hip breadth, seated, elbow to elbow breadth, and shoulder breadth for males and females based on the data in ISO 7250-2. The percent accommodated was determined by subtracting the average value for each dimension from 447.4 mm, then dividing by the appropriate standard deviation, and finally converting the resulting z-score to a percent value.

4.3.1. Estimation of concurrent accommodation

The procedure suggested by Albin and Molenbroek (Albin and Molenbroek, 2016) was used to estimate the concurrent accommodation for hip breadth and shoulder width and for hip breadth and elbow-to-elbow width.

In this approach, the measurement data for each dimension are treated as indicator function variables. An indicator function has a value of 1 or 0, depending on the outcome of some test. By definition, 90 percent of individuals have measurements less than or equal to the 90th percentile value, and the probability that any individual has a measurement less than or equal to the 90th percentile value is 0.90. If the indicator function test is whether an individual's measurement for some dimension is less than or equal to the 90th percentile value, then the probability that the indicator function will have a value of 1 for any individual is 0.90.

The probability that any individual is in the intersection of any two sets, e.g. the intersection between the set of individuals with hip breadths less than the 90th percentile hip breadth value with the set of individuals with shoulder breadth measurements less than the 90th percentile shoulder width value, can be determined by means of the formula $P(A \cap B) = (r_{AB}*sdA*sdB) + (P(A)*P(B))$ (Albin and Molenbroek, 2016).

In the equation, $P(A \cap B)$ is the probability that any individual will be in the intersection of the two sets, r_{AB} is the correlation between the two sets, $P(A)$ is the probability that an individual is in set A and $P(B)$ is the probability that an individual is in set B. The standard deviation of the indicator function A is indicated by sdA, and can be calculated as the square root of $[P(A)(1-P(A))]$; the standard deviation of B (sdB) is similarly determined.

The intersection of these two sets is interpreted as holding those individuals whose hip and shoulder breadths are both less than or equal to the respective 90th percentile values for hip and shoulder breadth. That is, if Jane's data are in the intersection of these two sets, then her hip and shoulder breadth measurements will both be less than or equal to the respective 90th percentile values of hip and shoulder breadth.

Since the average seat pitch of 816 mm accommodated users of both genders for all nationalities, the analysis performed in this paper was limited to estimating the proportion of individuals concurrently accommodated on both seat width and elbow-to-elbow breadth or seat width and bideltoid shoulder breadth. The results are shown in Table 3.

Table 3 also includes World Bank data (World Bank, 2016) on the number of airline passengers in 2014 and the estimated number of passengers who were not accommodated by the average seat design values reported by Seatguru (Seatguru, 2016).

4.4. Results

On average, about 32 percent of males and 78 percent of females from the seven nationalities represented in the ISO 7250-2 Technical Report are concurrently accommodated on both the seat and shoulder width by a seat space width of 447.4 mm. Concurrent accommodation on seat width and elbow to elbow breadth was about 35 percent for males and 65 percent for females. This latter estimate is limited to the six nationalities in the Technical Report for whom elbow to elbow breadths are available.

It is necessary to have some knowledge of the correlation between the variables in to calculate the probability that an individual is concurrently accommodated on the two width measurements. An average correlation value of 0.3 was used to develop the approximate proportions shown in Table 3. Since the actual correlation values were unknown, the proportion in the intersection of seat width and shoulder width was also calculated for correlation values of 0.1, 0.5 and 0.7. A correlation value of 0.1 resulted in

Table 2
Proportion of individuals accommodated separately on hip breadth, elbow-to-elbow breadth and shoulder breadth for a seat space width of 447.4 mm.

Nationality	Proportion Males Accommodated, Elbow-to-Elbow Breadth	Proportion Females Accommodated, Elbow-to-Elbow Breadth	Proportion Males Accommodated, Shoulder Breadth	Proportion Females Accommodated, Shoulder Breadth	Proportion Males Accommodated, Hip Breadth	Proportion Females Accommodated, Hip Breadth	Proportion Males Accommodated, Seat Pitch	Proportion Females Accommodated, Seat Pitch
Italy	0.130	0.538	0.314	0.923	1.000	0.996	1.000	1.000
Japan	0.719	0.986	0.315	0.973	1.000	1.000	1.000	1.000
Kenya	0.400	0.442	0.485	0.601	0.989	0.872	1.000	1.000
Korea	0.269	0.739	0.230	0.892	1.000	1.000	1.000	1.000
Netherlands	0.092	0.359	0.204	0.673	0.985	0.772	1.000	1.000
Thailand	0.504	0.921	0.521	0.966	1.000	1.000	1.000	1.000
USA	—	—	0.128	0.659	0.969	0.758	1.000	1.000
Average	0.353	0.664	0.314	0.812	0.992	0.914	1.000	1.000
Std. Dev.	0.238	0.258	0.145	0.161	0.012	0.112	0	0

Table 3
Proportion of airline passengers concurrently accommodated for shoulder breadth and hip breadth, sitting or elbow to elbow breadth and hip breadth, sitting, by an average airline seat space 447.4 mm wide, and the estimated number of passengers not accommodated annually.

Nationality	Proportion of Males Concurrently Accommodated, Hip and Elbow-to-Elbow Breadth	Proportion of Females Concurrently Accommodated, Hip and Elbow-to-Elbow Breadth	Proportion of Males Concurrently Accommodated, Hip and Shoulder Breadth	Proportion of Females Concurrently Accommodated, Hip and Shoulder Breadth	Airline Passengers in 2014 Based on World Bank Data	Number of Males Not Concurrently Accommodated, Elbow and Hip Breadth	Number of Females Not Concurrently Accommodated, Elbow and Hip Breadth	Number of Males Not Concurrently Accommodated, Shoulder and Hip Breadth	Number of Females Not Concurrently Accommodated, Shoulder and Hip Breadth
Italy	0.130	0.550	0.311	0.922	25,594,275	11,133,510	5,758,712	8,817,228	998,177
Japan	0.716	0.986	0.309	0.972	110,544,000	15,697,248	773,808	38,192,952	1,547,616
Kenya	0.408	0.432	0.491	0.569	4,792,267	1,418,511	1,361,004	1,219,632	1,032,734
Korea	0.267	0.736	0.225	0.889	59,067,351	21,648,184	7,796,890	22,888,599	3,278,238
Netherlands	0.100	0.334	0.213	0.574	33,928,613	15,267,876	11,298,228	13,350,909	7,226,795
Thailand	0.496	0.920	0.516	0.965	44,039,176	11,097,872	1,761,567	10,657,481	770,6865
USA	–	–	0.139	0.556	762,560,000	–	–	328,282,080	169,288,320
Average	0.353	0.660	0.315	0.778	148,646,526	12,710,534	4,791,702	60,486,983	26,306,081

average concurrent accommodation estimates of 31 percent of males and 76 percent of females, a correlation value of 0.5 yielded average concurrent accommodation estimates of 32 percent of males and 80 percent of females, and an average correlation value of 0.7 resulted in average concurrent accommodation estimates of 32 and 81 percent respectively for males and females, respectively. It appears that the accommodation estimate is relatively insensitive to differences in the correlation value.

Table 3 also estimates the number of passengers flying each year whose seat spaces do not completely accommodate them. The number of passengers in each country is taken from World Bank data (World Bank, 2016). Since no gender identification was available in the World Bank data, half the total number of passengers for each country were assumed to be male or female. Similarly, no data were available regarding the different nationalities flying within a given country, so the anthropometry pertinent to the country where the flight took place was used to determine accommodation. While any differences between these assumptions and the actual passenger characteristics would obviously affect the accommodation estimates, the data certainly give a useful depiction of the scope of the problem of seat width accommodation.

4.5. Discussion

The Seatguru data (Seat Guru, 2016) do not include the width from center to center of the armrests on seats. Consequently, some greater accommodation at the armrest and shoulder level will be realized by the extra space afforded by the width of the armrest.

Quigley et al. (2001) suggest using the maximum value of a dimension that is encountered in world anthropometry to determine seat space volume. Based on the 95th percentile values for all the nationalities reported in ISO 7250-2 (ISO, 2010), a width of 501 mm (19.7 inches) between the armrests would be necessary to accommodate every nationality's seated hip breadth, a seat space width of 571 mm (22.5 in) would be necessary to accommodate every nationality's elbow-to-elbow breadth and a seat space width of 550 mm (21.7 inches) would be required to accommodate 95 percent of every nationality's shoulder width. Thus, a seat width accommodating 95 percent of every nationality at armrest level would need to be about 124 mm (4.9 in) wider than the current average 447.4 mm width between armrests.

Applying the method described by Albin and Molenbroek (Albin and Molenbroek, 2016), the intersection (concurrent accommodation) of two 95th percentile measurements where the correlation value is assumed to be 0.3 is estimated to be about 92 percent. It is quite possible that these dimensions are more highly correlated, which would increase the proportion accommodated; Roebuck (Roebuck, 1995) suggests a correlation of approximately 0.7 between seat width and elbow-to-elbow breadth. However, the actual correlation data are unknown, so a conservative approximate overall average is used for illustration.

5. Anthropometry and accommodation in current and future airline seating design

Earlier it was noted that seat design variables, especially seated hip breadth, have been increasing at a rate of about 2–3 percent per decade for the past 30–50 years. Similar changes in seated hip breadth were found for the Dutch students over a period of about 30 years, further confirming this trend. Seating designers must take this trend towards increases in widths into consideration when designing seating intended to be used for decades into the future.

In contrast to changes in the width of seating spaces, the student data suggest that the buttock to knee length of Dutch males, which largely determine seat pitch requirements, have remained

relatively constant.

In addition to the impact on the future design of transportation seating, it was also shown that current seating space designs may not adequately accommodate a significant proportion of the intended users at present, a situation that will not improve if the trend towards increasing passenger widths continues.

These data examined in this paper suggest that, while a seat pitch of 816 mm appears to be effective in accommodating the current 95th percentile buttock knee length for all the nationalities described in ISO 7250-2 (ISO, 2010), the average seat space width of 447.4 mm is more problematic when compared to seated hip breadths.

A significant number of Dutch, Kenyan and American females are not accommodated by the 447.4 mm average seat width. Moreover, a seat space dimension of 447.4 mm is not efficient in providing sufficient accommodation for either gender's shoulder breadth or elbow to elbow breadth, whether considered independently or as concurrent accommodation with hip breadths.

Annex A. TU Delft anthropometric dimensional measurements and measurement procedures

1. Stature: the vertical distance from the floor to the top of the head (vertex) was measured while the subject stands erect, feet together and unshod, the head oriented in the Frankfort plane (equipment anthropometer)
2. Elbow-elbow breadth: maximum horizontal distance between the outside region of the elbow was measured while the subject sits erect with the popliteus against the edge of the sitting surface, the upper arms against the vertical surface, the elbows pressed against the torso and the forearms flexed perpendicular to the vertical plane (equipment anthropometer)
3. Hip breadth seated: breadth of the body measured across the upper leg's turning point of the hip while the subject sits fully erect with the thighs fully supported, the popliteus against the edge of the sitting surface, the knees are bent at right angles with feet flat on the supporting board. The subject is asked to lean forward when the back support is moved against the rearmost point of the buttock and locked in place (equipment anthropometer)
4. Shoulder breadth: distance across the maximum lateral protrusion of the right and left deltoid muscles while the subject sits erect with the popliteus against the edge of the sitting surface, the upper arms against the vertical surface, the elbows pressed against the torso and the forearms flexed perpendicular to the vertical plane (equipment anthropometer)
5. Thigh height: vertical distance from the sitting surface to the highest point on the thigh while the subject sits erect with the popliteus against the edge of the sitting surface. The knees are bent at right angles with feet flat on the supporting board (equipment anthropometer)
6. Buttock-popliteal length: horizontal distance from the edge of the sitting surf to the back rest measured while the subject sits erect with the popliteus against the edge of the sitting surface. The subject is asked to lean forward when the back support is moved against the rearmost point of the buttock and locked in place (equipment measuring chair)
7. Buttock-knee length: In the same position as mentioned at point 6 the distance between the most protrusive point of the patella and backrest is measured (equipment anthropometer)
8. Buttock-foot length: The distance from backrest to footsole measured while seated with the leg stretched. The subject is

asked to lean forward when the back support is moved against the rearmost point of the buttock and locked in place (equipment anthropometer)
9. Elbow height: The vertical distance between the lowest bony point of the elbow to the horizontal sitting surface while seated In the position as mentioned at point 6. The subject is asked to have the upper arm along the body and the lower arm horizontal (equipment anthropometer).
10. Eye height seated: vertical distance from a horizontal sitting surface to the outer corner of the eye, while the subject sits fully erect with the popliteus against the edge of the sitting surface. Head is oriented in the Frankfurt plane. The anthropometer is placed around 10 cm in front of the subject (equipment anthropometer)
11. Popliteal height sitting: vertical distance from the foot-rest surface (supporting board) to the lower surface of the thigh immediately behind the knee, bent at right angles. The subject holds thigh and lower leg at right angles when seated. The measurer moves the supporting board upwards until it supports the feet and locks it in place. A measuring scale on the vertical axis of the chair indicates the distance between the support board to the horizontal sitting surface (equipment: measuring chair)
12. Sitting height: vertical distance from a horizontal sitting surface to the highest point of the head (vertex), while the subject sits fully erect with the popliteus against the edge of the sitting surface. Head is oriented in the Frankfurt plane (equipment anthropometer)

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