Computer-aided evaluation and improvements for car controls

Contents

Introduction

A car design has been presented for analysis using computer-aided ergonomics (CAE) techniques to determine its suitability for Asian and European markets. The main information required is the range of drivers that could effectively drive the car, and whether any controls are in need of relocation. The scope of this investigation extends to the usability of car controls.

Relevant constraints on control use include:

- Clearance: 1-way constraint - limited by the largest
- Reach: 1-way constraint - limited by the smallest
- Posture: 2-way constraint - maximum angle deviations in both directions

The limiting users at each end can be found, leaving the range between capable of effective use, however defined. (Pheasant and Haslegrave, 2006)

Computer-aided ergonomics provides a quick and cheap method for validating designs and finding obvious faults. SAMMIE has built-in methods for creating and posturing human models with anthropometrics based on built-in datasets or custom measurements (Porter *et al.*, 1993)

This investigation aimed to understand driver posture and control use via triangulation from a range methods balancing internal and ecological validity, and then use this to define effective use. The range of driver sizes could then be determined, control positions evaluated, for improvements in a redesign.

User Research/Existing behaviour

Participants

Given that the 2-way constraints on design were expected to be due to limb length, the most important criterion in participant selection was heterogeneity in this dimension between participants. As such, stature was used as a filter, ensuring that there were participants at both ends of the size spectrum. Age and sex were secondary sampling requirements, as some studies have suggested these influence sitting posture (Schmidt *et al.*, 2014).

Potential participants were approached and asked if they would be interested in participating, before they were presented with the information sheet (Appendix A and consent form (Appendix B). 9 participants were involved in at least one aspect of the study, 6 male, 3 female, 6 18-25, and 3 50-55 (Table 1).

#	Sex	Age	Years with License	Number of car models driven	Days driven per month	Typical Journey Length (min)
1	M	18	1	6	28	40
2	M	22	4	2	30	20
3	M	19	1	1	13.5	60
4	M	21	3.5	2	25	20
5	F	23	4.5	1	30	80
6	F	18	1	2	28	20
7	M	51				
8	M	53	35	30+	30	75
9	F	53	36	10+	8	30

Table 1: Participant information (7 did not return the questionnaire)

Observation

A participant was observed during 2 greater-than-1 hour drives, one during the daytime in dry weather; one during nighttime in the rain. This was helpful to provide a range of contexts in which the task is performed.
The frequency of control use was observed (Appendix C), and an initial HTA was created for further validation/refinement later on.

Interview

Semistructured interviews were carried out, with questions on control and general car use as well as more direct validation and refinement of HTA. The HTA was finalised and created in a tabular format, as described by (Shepherd 1998, 2001; Shepherd and Stammers 2005; Stanton 2006) (Appendix F)

Questionnaire (Appendix D)

A questionnaire was written, following guidelines from Robson and McCartan (2015), to determine the significance of car controls using 3 measures. Frequency was measured on a 0-5 scale, with each number approximately an order of magnitude larger than the one before (factor ~6).
Importance was determined by classifying controls as “primary”, “secondary”, or “tertiary” (where primary is the most important), and each was also evaluated as a binary “essential” or not.

Pilot Posture Capture

Schmidt *et al*., (2014) found some studies suggesting class of vehicle influences posture. A 2004 model Renault Clio was the car that was most similar to the digital one and available at the same time as participants. The pilot was used to test the posture capture methodology, and compare photographic and goniometric joint angle measurement.

The camera used was a Canon 7D (on a tripod) with a 28mm lens, which closely represents the central 40-60° field of view of humans with the least apparent distortion (McHugh, 2005; Peñaranda, Velho and Sacht, 2015).

The methodology was influenced by Porter and Gyi (1998), using 2D joint angles and markers on the same joint landmarks. This was typical of the studies in the meta-analysis by Schmidt *et al.* (2014). Photographs were taken from the driver side, but it became clear more angles were needed.

When foreshortening was visually accounted for, measuring joint angles with a photo was sufficiently as accurate as with a goniometer. The technique was also much faster, most importantly for the participants.

'Normal' driving posture was much more upright than observed previously. When participants were asked how they would sit after 20 minutes driving, this discrepancy was no longer noticeable.

Posture Capture and Anthropometry

The posture capturing process was similar to the pilot, but applied the lessons learnt:

- Additional joint markers were used that would map to SAMMIE's pin joints.
- Postural photos were taken from 3 main angles - left, right and front.
- For the right side shot, the camera distance was 200cm from the participant's hip, aligned with the hip vertically and horizontally to minimise parallax errors with this important joint (Schmidt *et al.*, 2014).
- The left side shot was the same, but aligned with the shoulder.
- A vertical plumb was hung from the ceiling for reference.
- Separate photos of the feet and hands were taken.

- Joint angles were determined using GIMP (GNU Image Manipulation Program) (Figure 1)

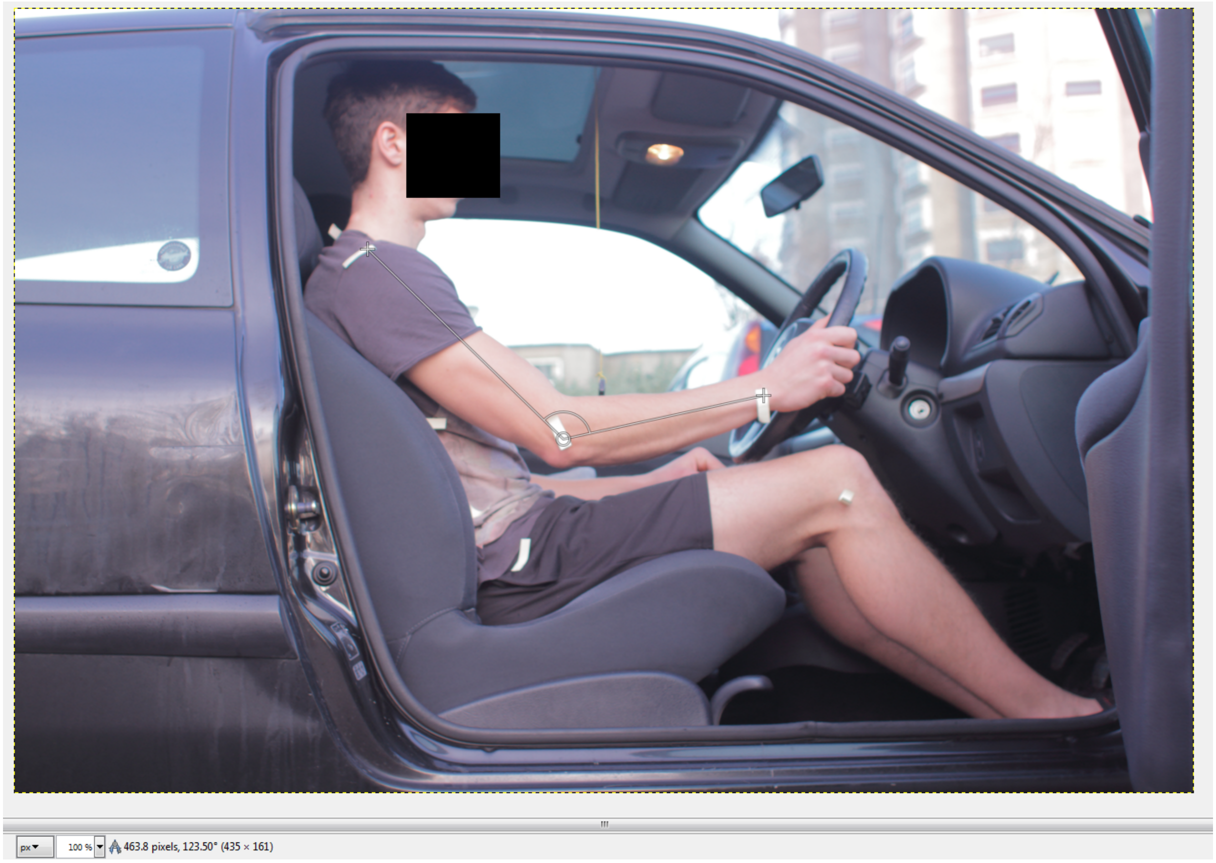

Figure 1: Screenshot showing elbow angle measurement based on joint landmarks using GIMP. Yellow line near centre shows plumb line

5 postures were adopted to provide the most important controls, and a range of distances and grip types:

- Normal driving after 20 minutes (relaxed)
- Using the gear stick
- Using the handbrake
- Using the temperature control
- Using the hazard lights

The dimensions measured were those SAMMIE uses in mannequin creation (again using the methodology described by Peebles and Norris (1998)), otherwise, the participants had their dimensions measured as in the pilot, but with a metalworking square pressed against a metre ruler. This minimised parallax error and the effect of tape bending.

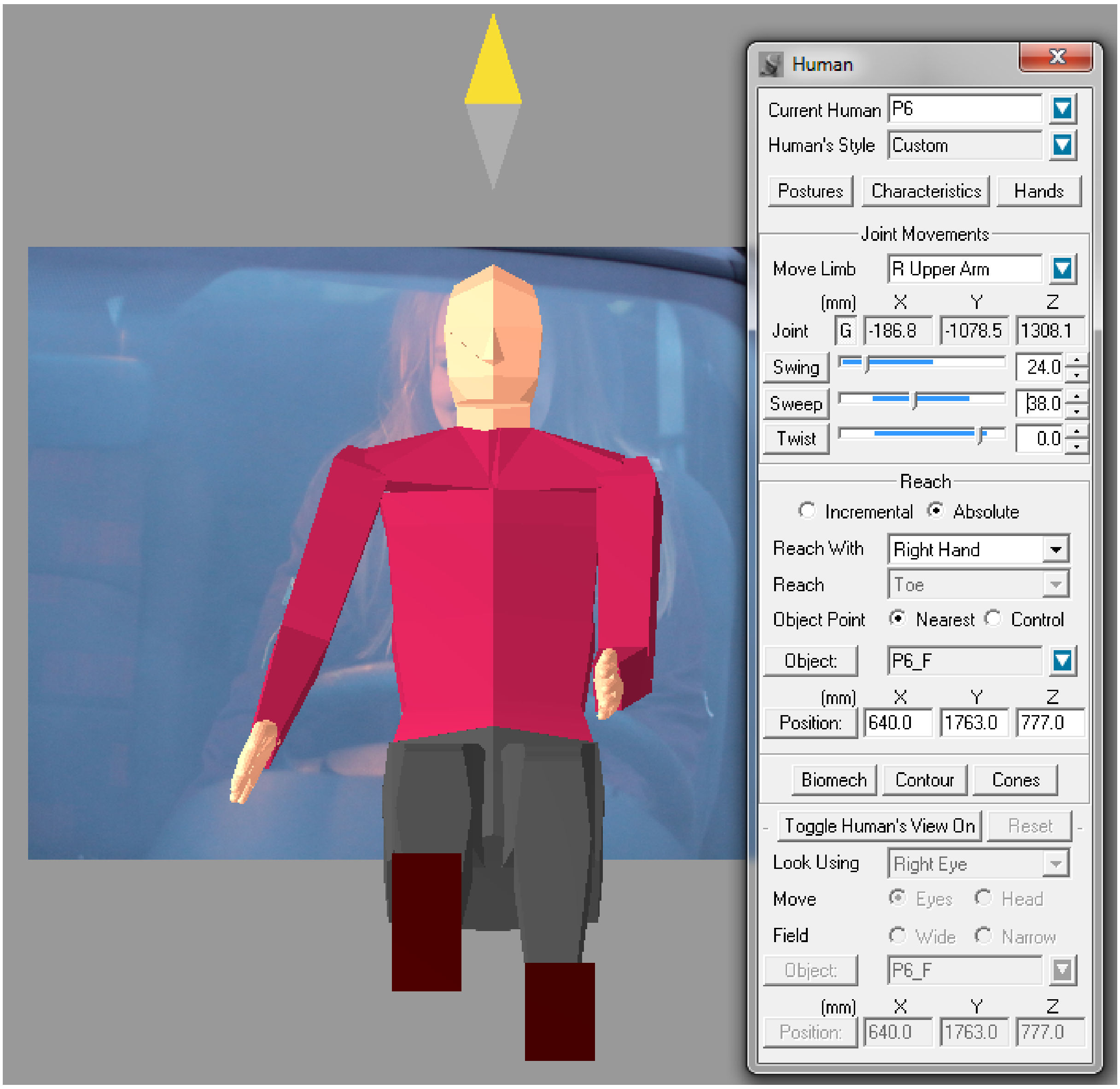

Figure 2: Part way through the process of recreating a participant's posture

Results

Posture and contact points

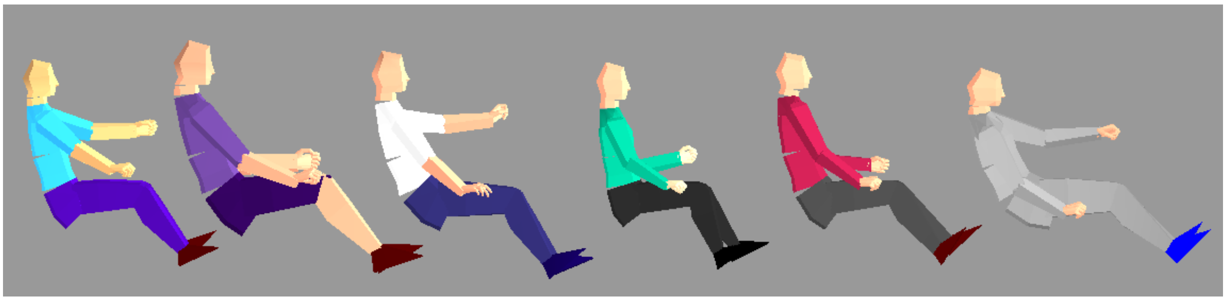

Figure 3: The recreated gear change posture for all measured participants

Contact points:

- Accelerator heel on floor
- Back on seat
- Hands used to operate all controls other than pedals

Posture:

- The pelvis tended to be significantly reclined
- Upper thighs were at or above horizontal
- Back curvature was concentrated more in the lumbar spine than the thoracic
- Hand position on steering wheel varied a lot, independent of participant size.
- For primary driving controls, only the sternoclavicular joint and those more distal moved compared to the normal driving posture
- Taller participants (and men) tended to have a more reclined posture, as in Schmidt *et al.* (2014).

Grip

The photographs of grips, as in Figure 4 were used to determine the grips required for those controls as well as those similar:

- Medium power grip: wheel, gearstick
- Small grip thumb out: handbrake
- Small pinch grip: all dials, ignition
- Relaxed hand: hazard button press

Figure 4: Typical grips for different controls: A) driving, B) gearstick, C) handbrake, D) temperature, E) hazard light

Design evaluation

Population

The client has, in discussion, suggested an Asian and European market. Pheasant and Haslegrave (2006) suggest that not only are Asians smaller on average across measurements than their European counterparts, their proportionality is different. They tend to have a smaller limb to torso size ratio. As the constraints are 2-way, limiting users must be found from both ends of the size spectrum. As such, the databases that shall be drawn from will be from the Chinese and Dutch populations. This is based on data suggesting that Chinese tend to be the smallest population, and the Dutch the largest (Pheasant and Haslegrave, 2006), and so models across both sets of data should accommodate the other nationalities in between. Additionally, men tend to be larger than women in most dimensions (the notable exception to this is hip breadth) (Pheasant and Haslegrave, 2006; Peebles and Norris, 1998).

Protocol

Limits were defined as final point at which the condition is acceptable.
Throughout the evaluation, the mannequins were created as either a univariate percentile or with nationality-based absolute measurements and positioned in the car following the same protocol. If any requirement was not achieved, the dimensions of the mannequin were considered outside the limits of the vehicle.

Setup - Positioning and posturing

1. Initially, mannequins had the posture of participant most closely matching their dimensions applied to them.
2. An appropriate seat height and seat-back were chosen.
3. The H-point of the mannequin was matched with the H-point of the seat, and this was ensured to be inside the H-point envelope.

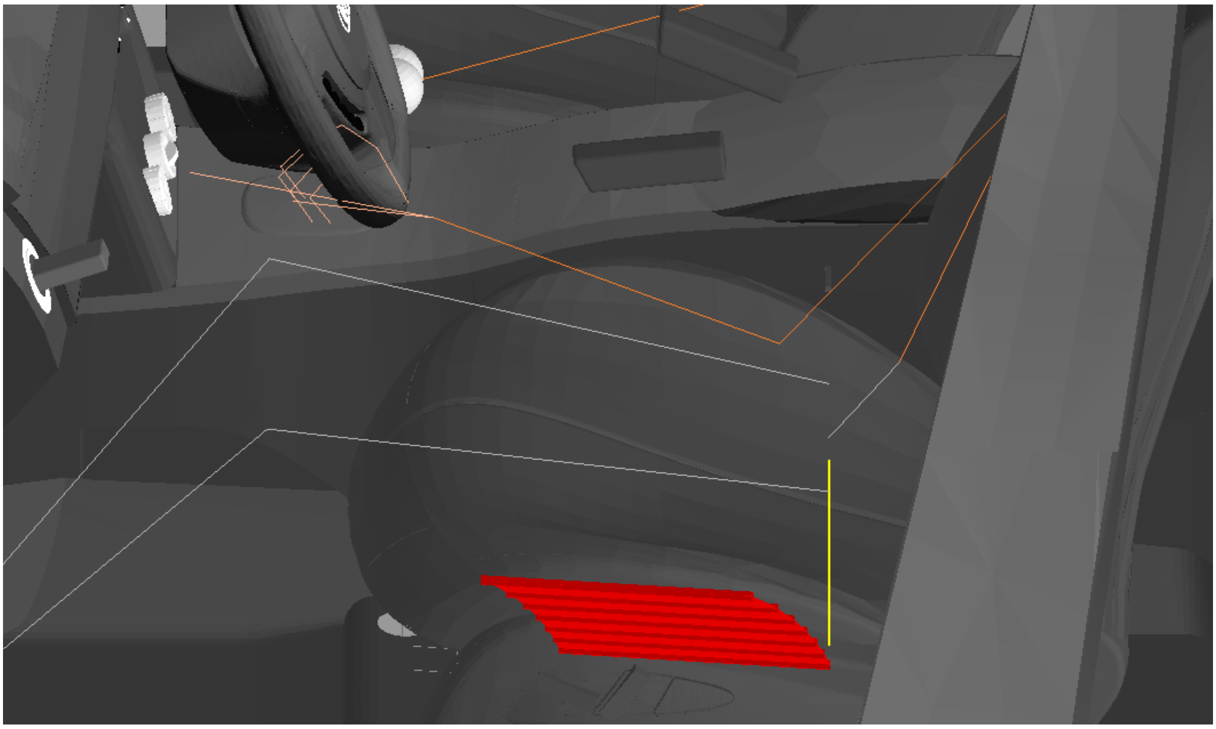

Figure 5: DM90 hip aligned with seat H-point (yellow line) at the back of the H-point envelope (in stickman view)

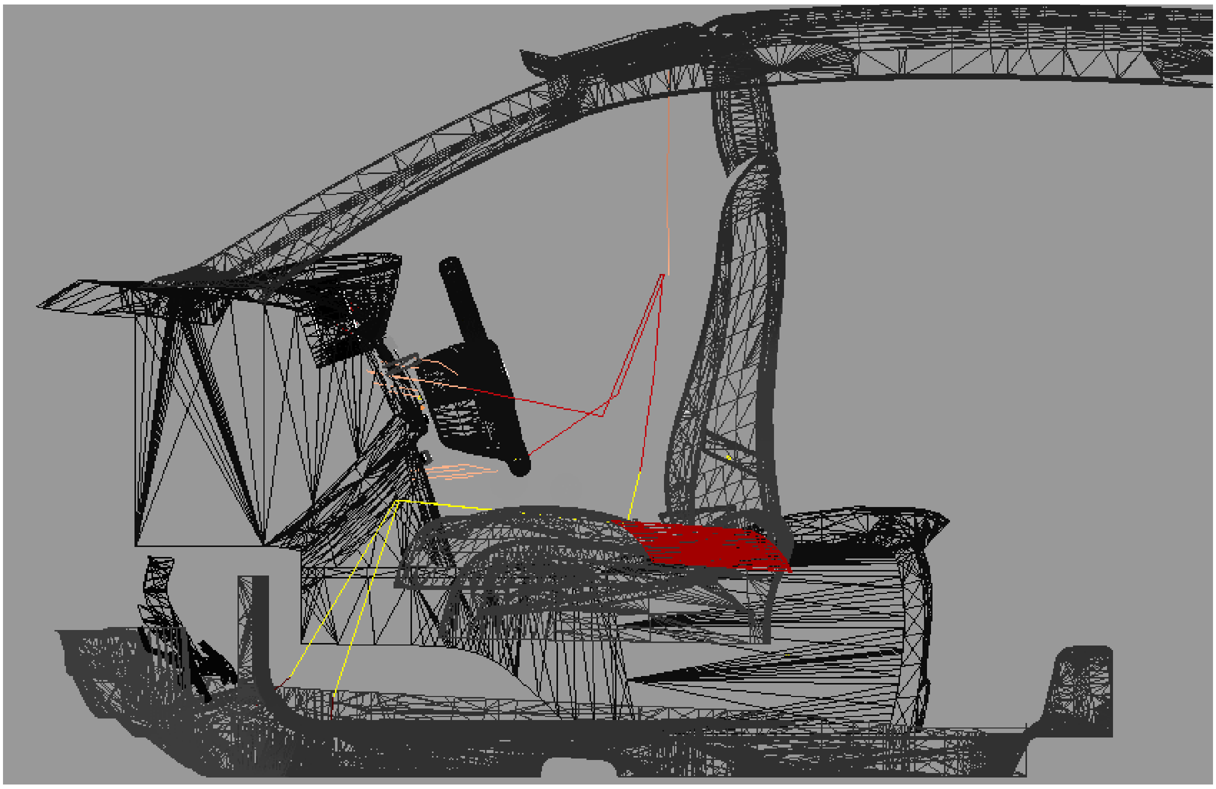

Figure 6: Ensuring the hip is inside the h-point using the parallel view from the left, with stickman view in wireframe

4. Seat fore/aft position (with mannequin attached), limb angles (legs and arms), and steering wheel position/angle were iteratively balanced with the aims:
    a. The right heel on the floor (AHP), foot covering half the accelerator
    b. Left foot contacting the clutch
    c. Left hand on steering wheel, right on gearstick

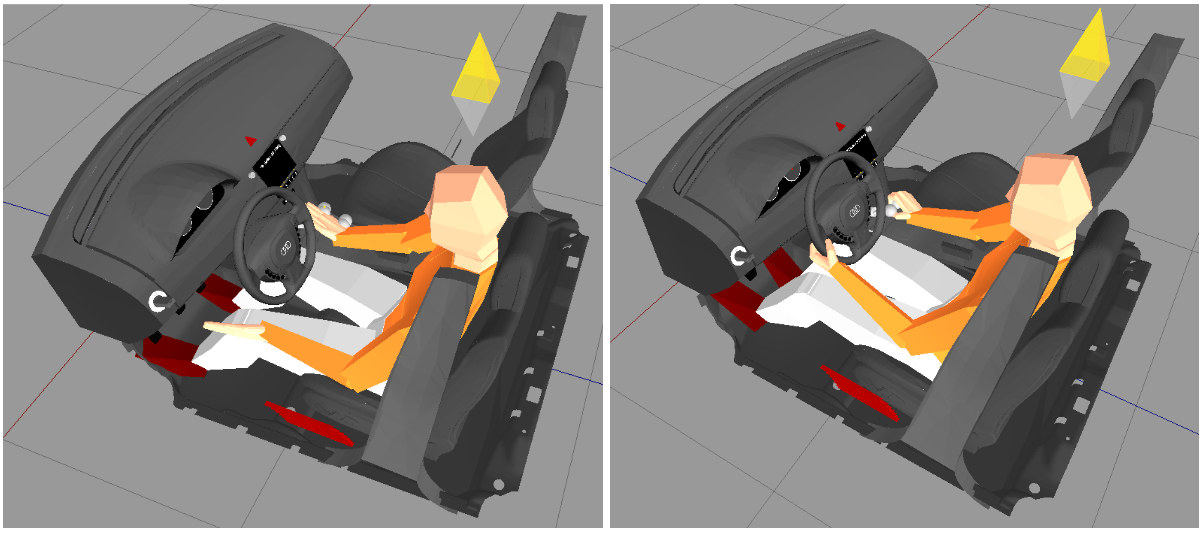

Figure 7: A) similar participant's posture on D90, B) adjusted to fit

Joint Angles

SAMMIE provides an internal set of joint angle constraints and comfort limits based on Barter, Emmanuel and Truett (1957). This is based on young males in the military, and so may not be appropriate for this task. Kee and Karwowski provide 'joint angles of isocomfort' (JAIs) and joint limits for males (2001) and females (2004). JAIs are the ranges within which a certain comfort level is maintained. For frequently used controls (mean ≥ 4 on the questionnaire), the required comfort was 'good' and for less frequently used controls was 'marginal'. The 50th percentile value was used for each joint of each gender, as the next comfort level down would just be acceptable for use at the given frequency, and to do otherwise would have been too constricting. Comfort is important, but a softer limit than others. Doriot and Wang (2006) was also consulted to determine any significant effects of age. The joint-angle degrees of freedom SAMMIE provides in the 'Human' window (Figure 2) predominantly correspond with those measured by Kee and Karwowski (2001, 2004).

Head Clearance

Abbas *et al.* (2013) found that, assuming an optimal suspension design, the whole body vibration caused by driving vertically displaces the driver's head upward with an amplitude of approximately 40mm from the normal sitting position. As such, this will be considered the head clearance limit for effective use, (without requiring a change of posture). The measurement utility determined the head clearance needed.

Reach

Reach was screened for using reach volumes that were attached to the mannequin's shoulder for all the grip types used. If the control was inside the volume, they were postured as if they were using it, sometimes using SAMMIE's inverse kinematics reach system to provide a starting point. If the control was outside the window, the acceptability of the shoulder protraction and torso flexion required was determined.

Vision

The visibility of controls was mostly determined using the 'Set human view' function.

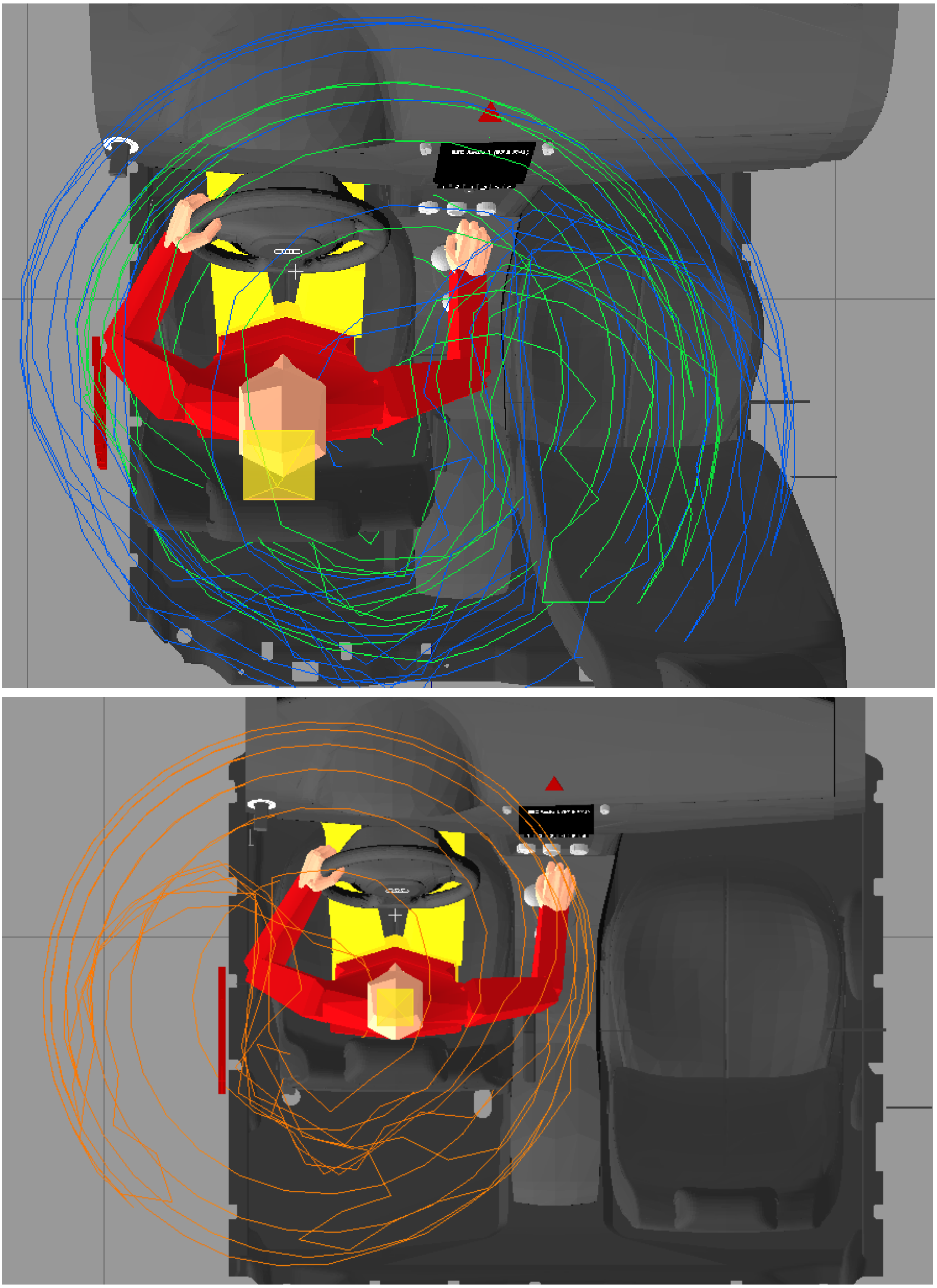

Figure 8: A) Reach contours for palm grip (green) and fingertip (blue) for the right hand of C10. B) For the left thumb grip (orange). These were attached to the shoulder to move with reposturing.

Requirements for effective use

The population that can 'effectively' drive a car will vary drastically based on the operationalisation of 'effectively'. The requirements were determined by a combination of the primary research described earlier and existing literature on automotive posture evaluation.

- Hip at H-point of the seat, in the H-point envelope (Figures 5, 6)
- Head clearance ≥40mm
- Back touching seat
- Able to see and reach all controls operated while driving that were considered necessary by more than half of the respondents, with the typical grips used in observation:
  - Steering wheel held with a medium palm grip
  - Handbrake in up position held with a medium palm/thumb out grip
  - Gear stick in neutral held with a medium palm grip
  - Hazard light pressed with the middle finger of a relaxed hand
  - Foot able to fully depress clutch (contacting it in the 'down' position)
- Accelerator heel on floor (Philippart *et al.*, 1984; Loczi and Dietz, 1999; Parkinson *et al.*, 2007)

Univariate Accommodation Limits

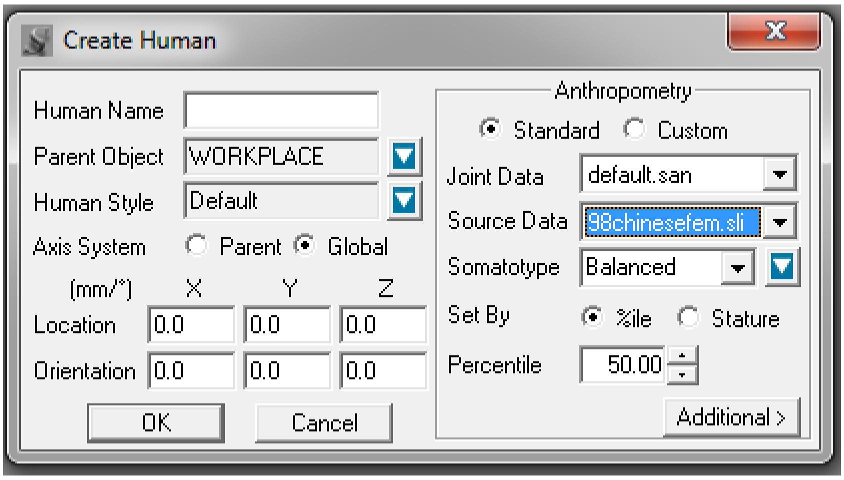

Figure 9: Creation of models in SAMMIE

Smallest User

The initial test mannequin for smallest user was 10th percentile Chinese female (CF10). This was tested with all the requirements, 2 of which it failed: shoulder angle comfort using the handbrake and accelerator foot on both floor and pedal.

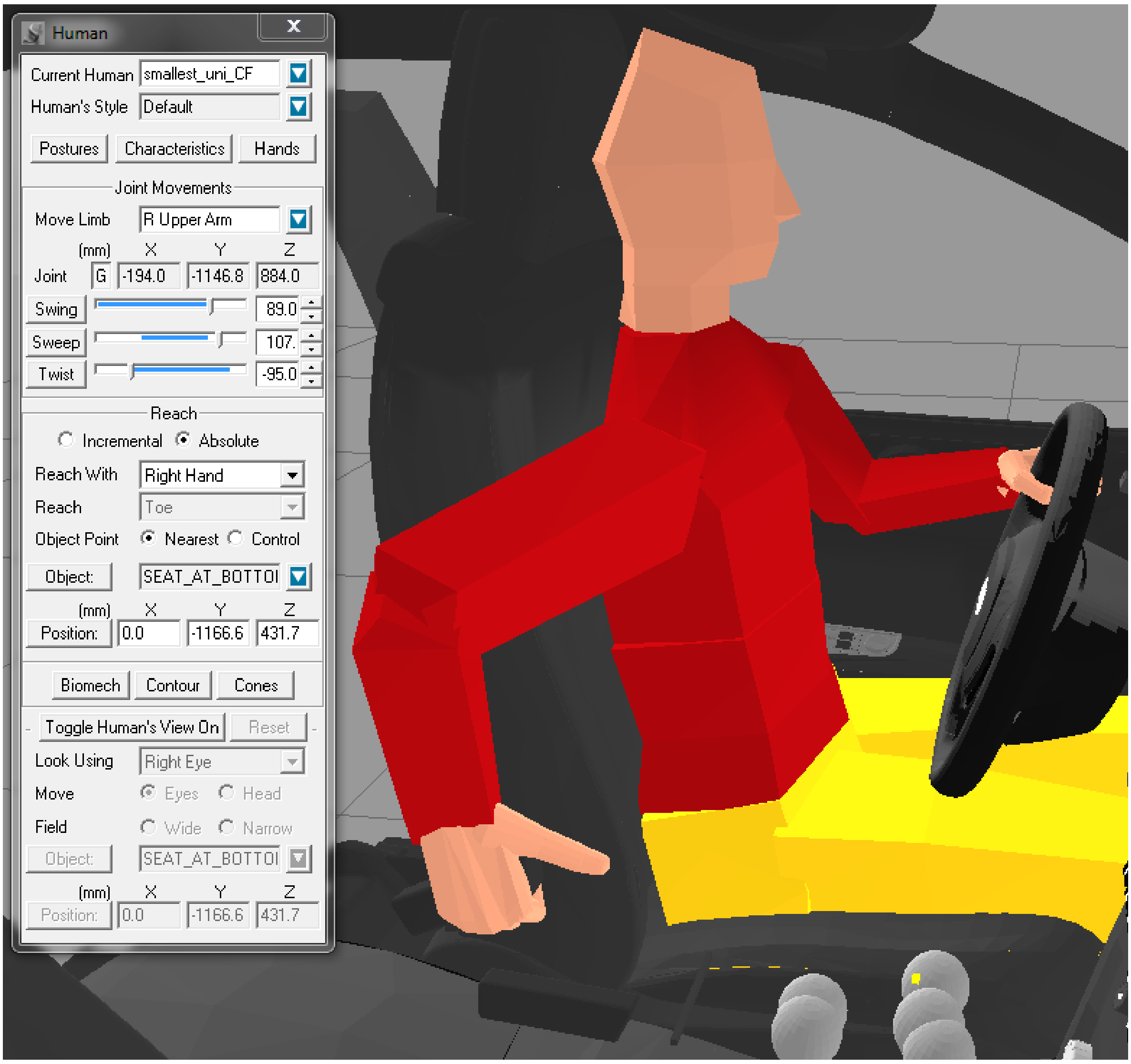

Figure 10: Shoulder significantly outside comfortable range

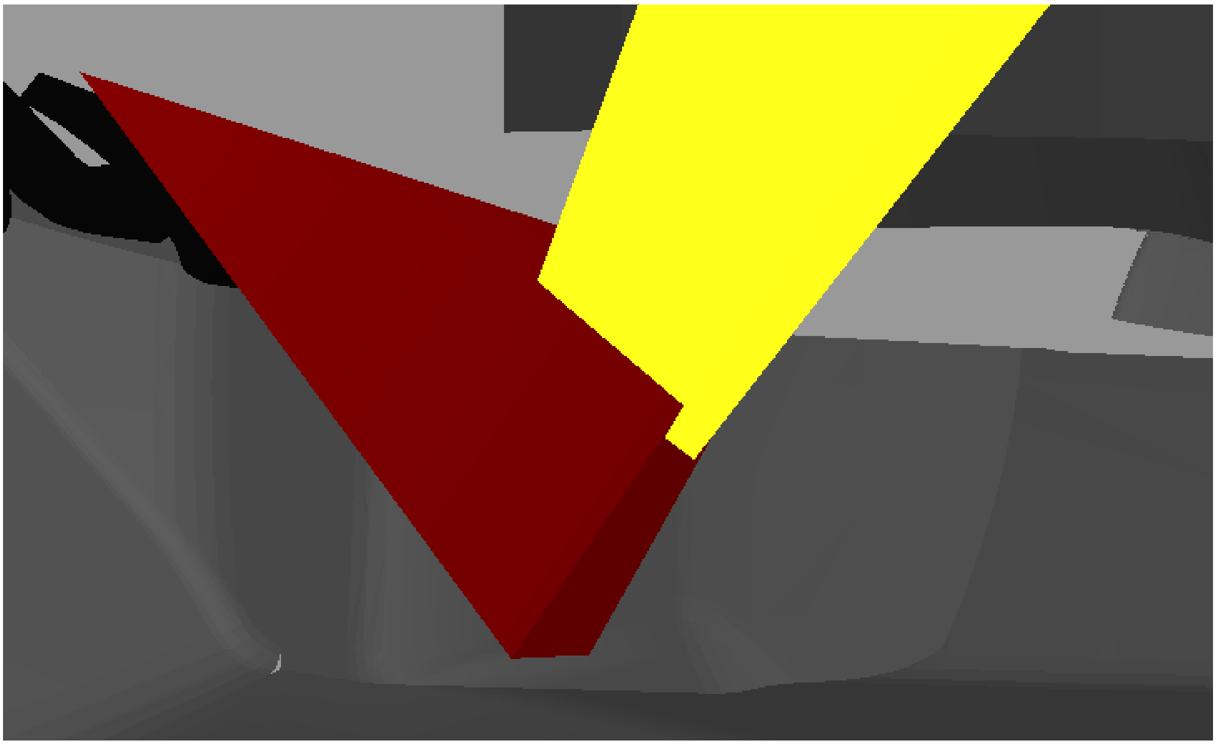

Figure 11: Pedal and floor not both reached by CF10

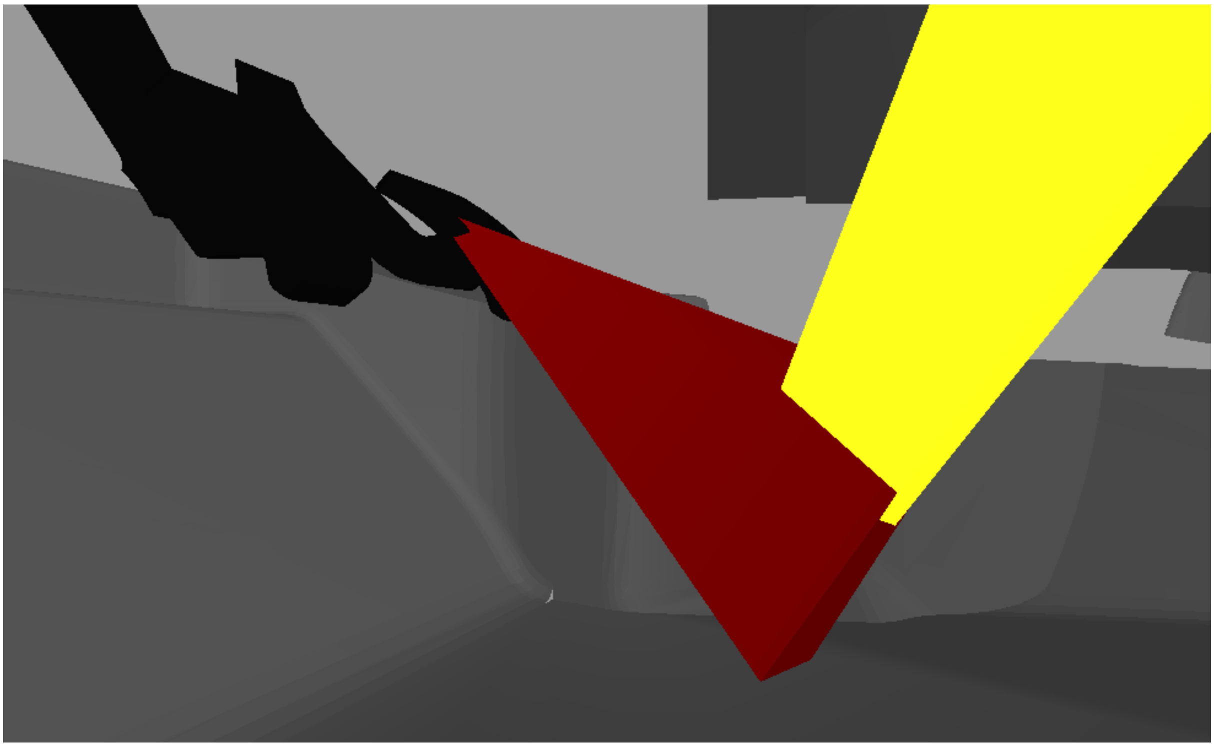

Figure 12: Pedal and floor both reached by CF60

The pedal-floor requirement was slightly less clear-cut - joint angles changed with univariate size. The smallest model to clearly meet this requirement, along with the others, was 60th percentile Chinese female (CF60).

Largest User

The initial test mannequin was the 90th percentile Dutch male (DM90). The limiting factor was head clearance. The univariate percentile was adjusted until the head clearance was ≥40mm. This was the case at DM84 with 43mm head clearance.

Dutch male percentile	**Head clearance**
90	30
87	36
85	38
84	***43***
82	44

Table 2: Univariate DM head clearances >40mm

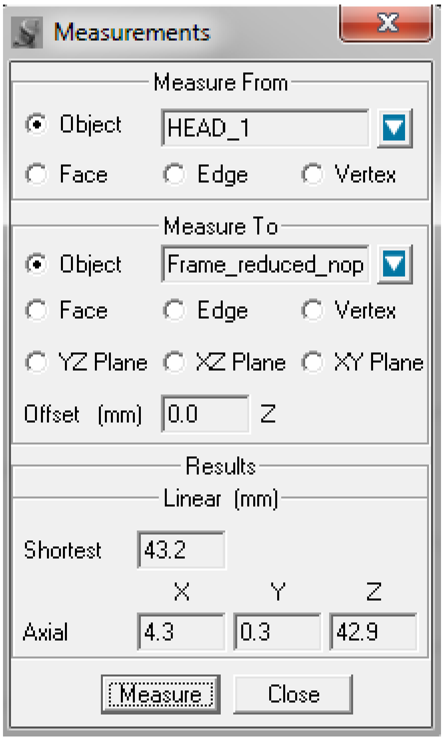

Figure 13: DM84 head clearance

The remaining requirements were then checked for DM84, all of which were acceptable. To use the handbrake comfortably, DM84’s elbow may have bothered a passenger.

Figure 14: DM84 gear

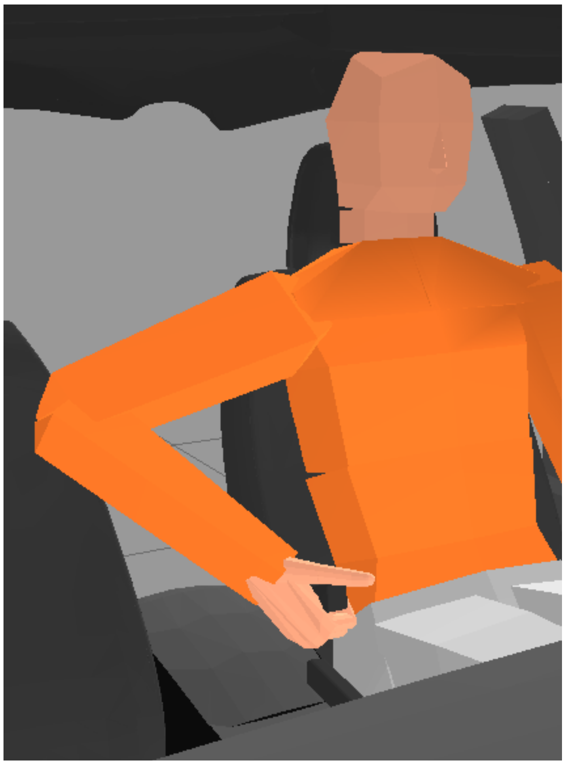

Figure 15: DM84 Handbrake

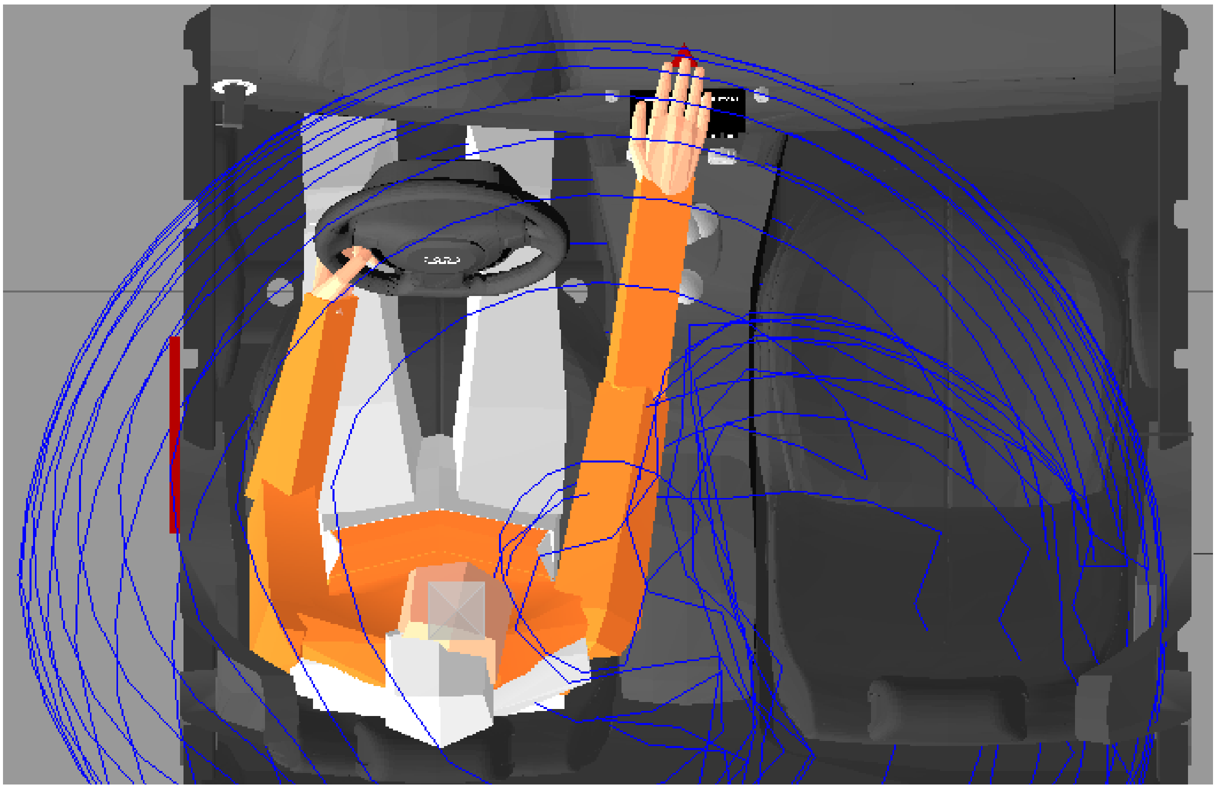

Figure 16: DM84 leaning slightly toward hazard light, and right hand finger reach volume

Multivariate control position analysis with A-CADRE

Some issues with the controls had been found with the univariate mannequins, but as Ziolek and Wawrow (2004) explain, analysis using univariate anthropometric percentiles is insufficient given the diversity of proportionality of most populations. Bittner (2000) provides a solution based on factor analysis of diversity of the general population. A family of 17 sets of dimensions, each with different proportions is presented, which are given as a percentile, so they can be mapped onto any population.

Given the aim to challenge the control positioning, models that would be expected to find use difficult were preferred. As fit was not as important here, constraints were relaxed. The usefulness of multivariate models is primarily due to the intra-model variance between multiple dimensions that make controls harder to use. The 17 A-CADRE models were stripped of the dimensions not used in the creation of SAMMIE models. As each dimension is normalised in the range 0-100 (as a percentile), intra-model dimensions can be directly compared. As a first pass toward deciding which mannequins would be most useful, the range and standard deviation of their dimensions was calculated. They were then put in descending order by range (Appendix H).

The A-CADRE models chosen were 8 and 9, represented as Dutch males (A8DM, A9DM) and 11 as a Chinese female (A11CF). Reasons are presented in Table 3. Dimensions were converted into mm using data from Peebles and Norris (1998).

Table 3: A-CADRE choices cover difficulties for controls in all areas

Model	**A8 Dutch Male**	**A9 Dutch Male**	**A11 Chinese Female**
Image			
Key Features	Short limbs, long torso, wide shoulders	Long limbs, short torso, narrow shoulders	Long legs, short torso, mid-length arms
Reasons/ Expected Difficulties	(Joint) largest variation The long torso, wide shoulders and short arms should provide clearance issue for controls on the door side given small space for adjusting.	(Joint) largest variation Difficult angle for controls behind gearstick Long limbs may put wheel in an awkward position.	Additional difficulty reaching farther controls, particularly those near the top of the dashboard
Nationality Choice	Having a long torso and wide shoulders was the priority	Having long limbs was the priority.	Having a shorter torso and arm length was the priority

Reach Issues

The most limiting controls in each section were tested for reach. As ideal control positions would not require leaning from the standard driving position, the distances by which controls were out of reach (using an appropriate grip) are collated below:

Table 4: Nearest surface out-of-reach distances (mm) for each mannequin

Control	**CF60**	**DM84**	**A8DM**	**A9DM**	**A11CF**
Hazard light	(in reach)	24	33	(in reach)	15
Ignition		13	(in reach)	(in reach)	(in reach)
Temperature control	(in reach)	65	90	22	50
Volume	(in reach)	70	84	38	56
Frequency	(in reach)	32	37	5	(in reach)
Central controller	(in reach)	36	54	(in reach)	(in reach

No controls were outside the mannequin's reach with sufficient leaning, tilting and/or shoulder protraction (Figures 17, 18)

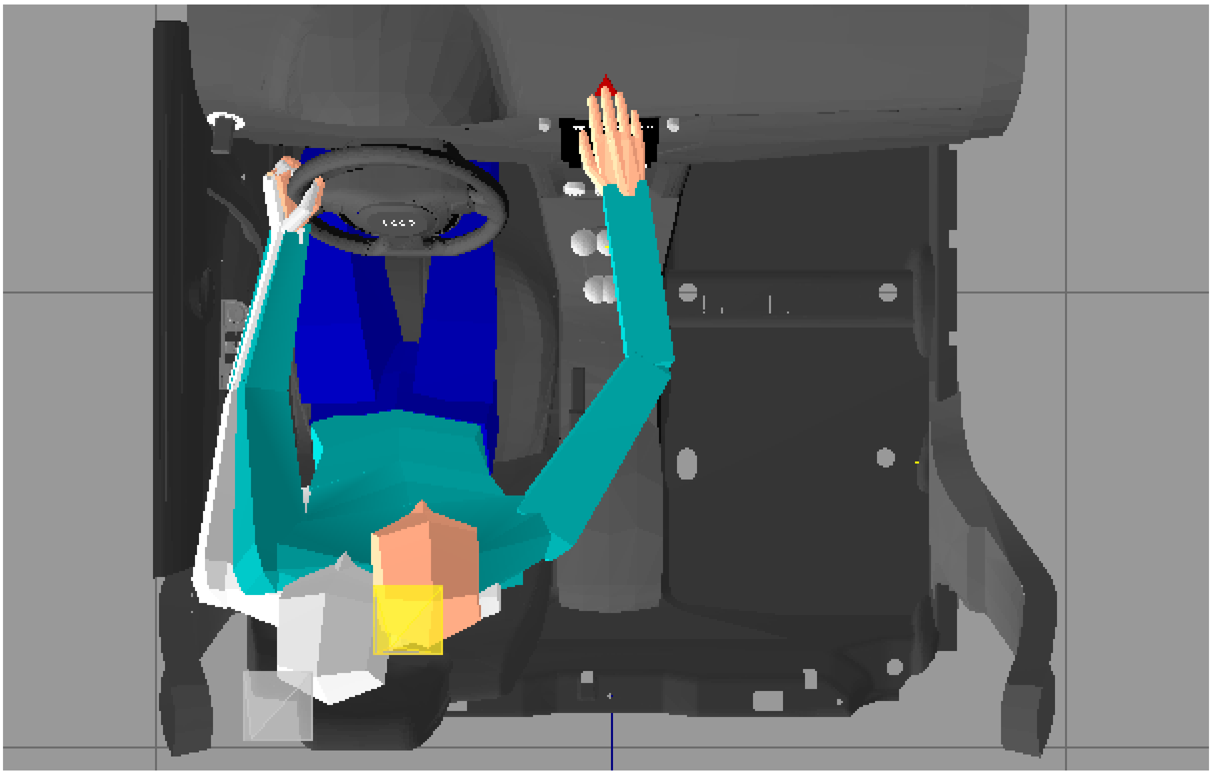

Figure 17: A9DM normal position (light grey) and bending and tilting to reach the hazard light

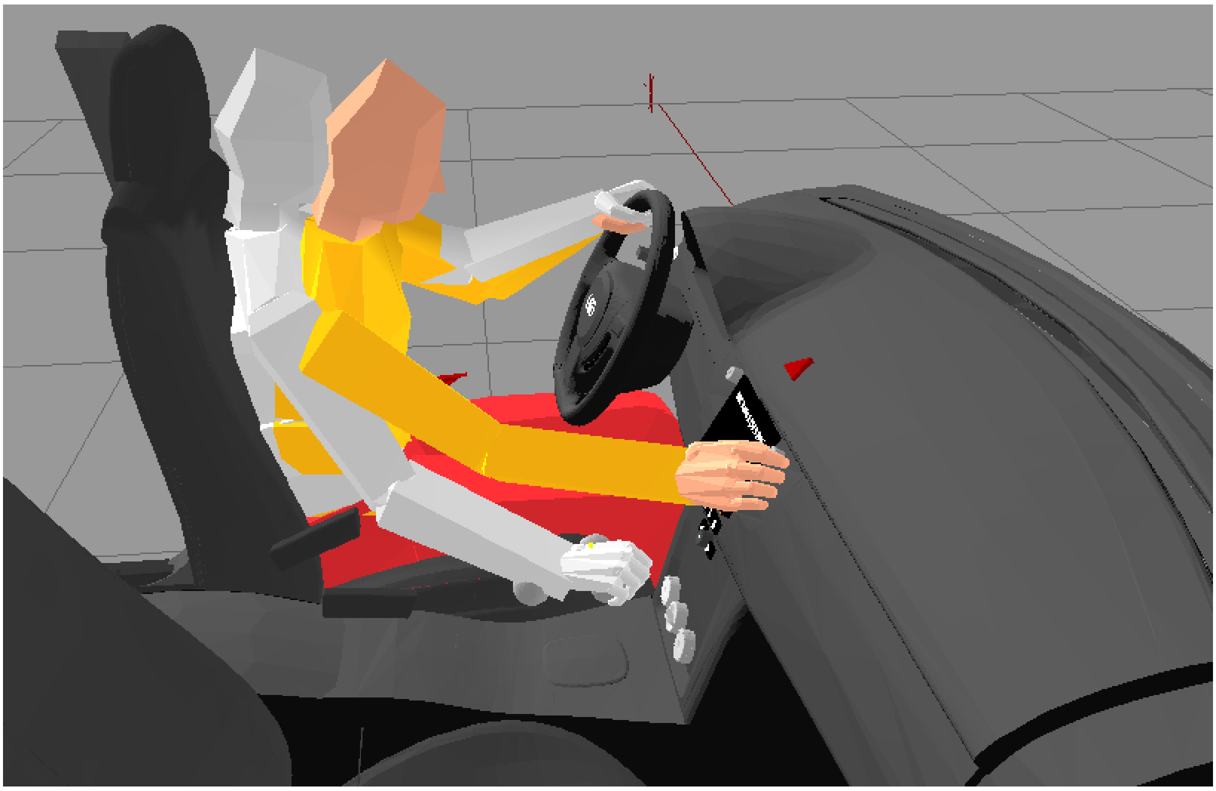

Figure 18: A11CF normal position (light grey) and bending and tilting to reach the volume dial

Posture issues

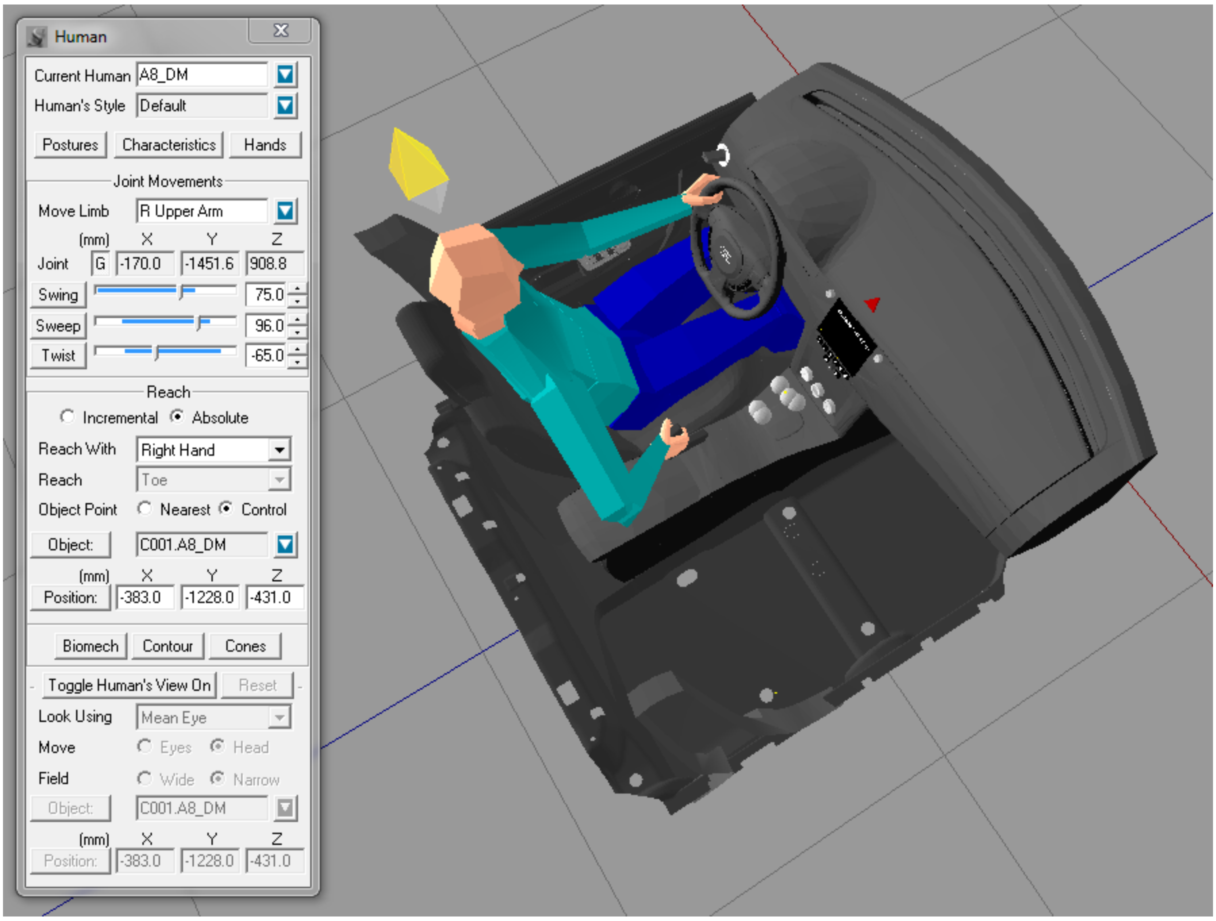

Figure 19: Shoulder position when using handbrake could be much more comfortable

Clearance issues

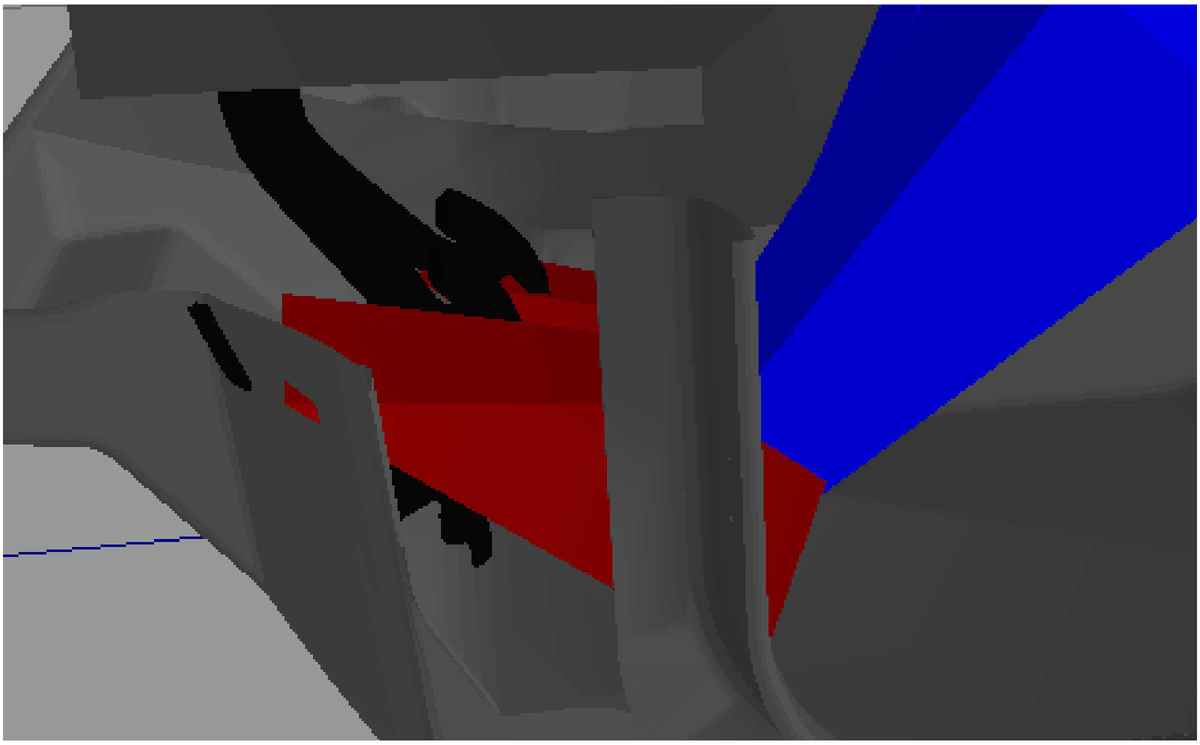

Figure 20: Pedals too far to the left force the foot against the side of the footwell

Figure 21: The low position of the HVAC controls means they are obstructed by the gearstick

Figure 22: from A9DM's view, temperature control is hidden. Steering wheel starts to clip legs at preferred distance

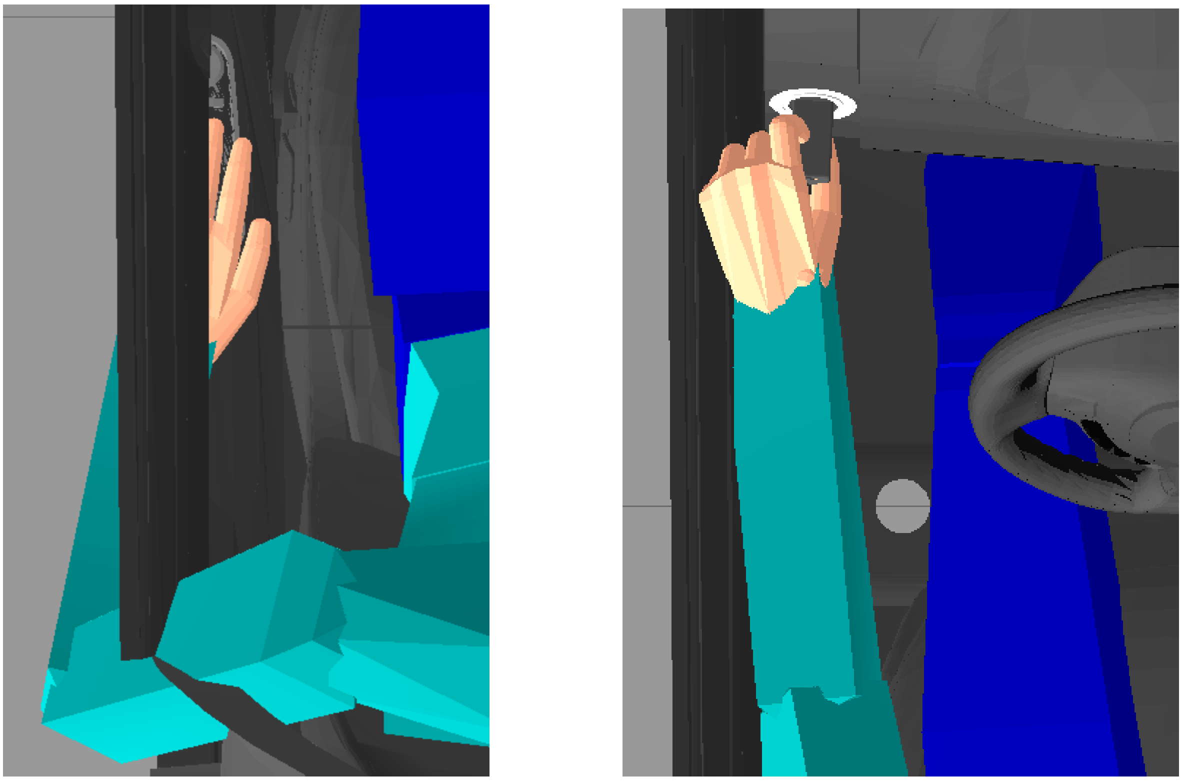

Figure 23: insufficient clearance from door in using window controls and ignition

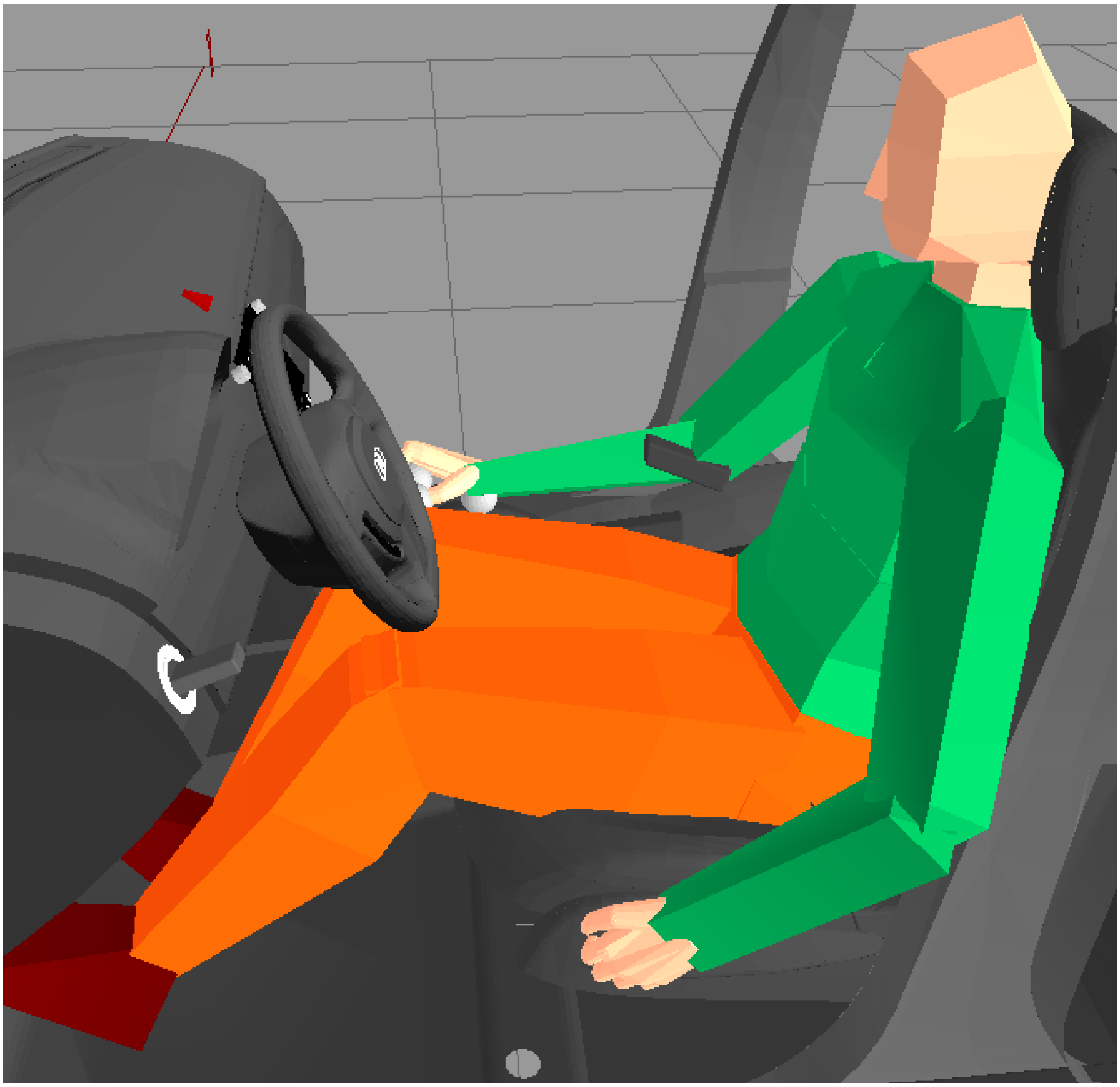

Figure 24: A9DM operating the seat control

All models could operate the seat control but were obstructed by the door.

Fortunately it is used at the beginning of a trip, optionally before shutting the door

Evaluation Conclusions

The range of people that are accommodated to drive effectively in the car model provided is 60th percentile Chinese female to 84th percentile Dutch male.

Additional control usability considerations include:

- Handbrake is too far back
- HVAC controls are too low, the gearstick is in the way, particularly for the temperature control
- Pedals are too high and too far left, many can't get heel on ground easily
- Window controls are awkward to reach so far back
- Ignition is too close to the door
- All mannequins were able to adjust steering wheel to comfortably reach it and see through to the dials, but all had it on the higher end of its range and A9DM had clearance issues from long legs even at the top end.

Design Changes

Sanders and McCormick (1993: 457) provide 4 general principles by which to group and locate functional components and controls:

- Importance ∝ convenience of location
- Frequency-of-use ∝ convenience of location
- Functional grouping - controls that affect the same part of the system should be grouped
- Sequence-of-use - positioning should reflect pattern of use (where appropriate)

The location of controls is convenient when they are closer to the operator and are easy to see, without obstruction.

Importance and frequency of use were quantified by questionnaire responses and so could be combined together to provide a control-location convenience weighting. Both were superlinear numbers, and lower numbers meant controls were more important (see Appendix D). The guideline weighting was created with the formula:

$$weight = 2 \times \frac{frequency^2}{importance^2}$$

This outputs a number in the range 0-100 (Appendix E), which was to be used to guide, but not replace, judgment of locations. An additional factor not included in the quantification is the danger presented by use of the control. For example, if the control is to be used while driving, it should be easier to see and reach.

Key Driving controls

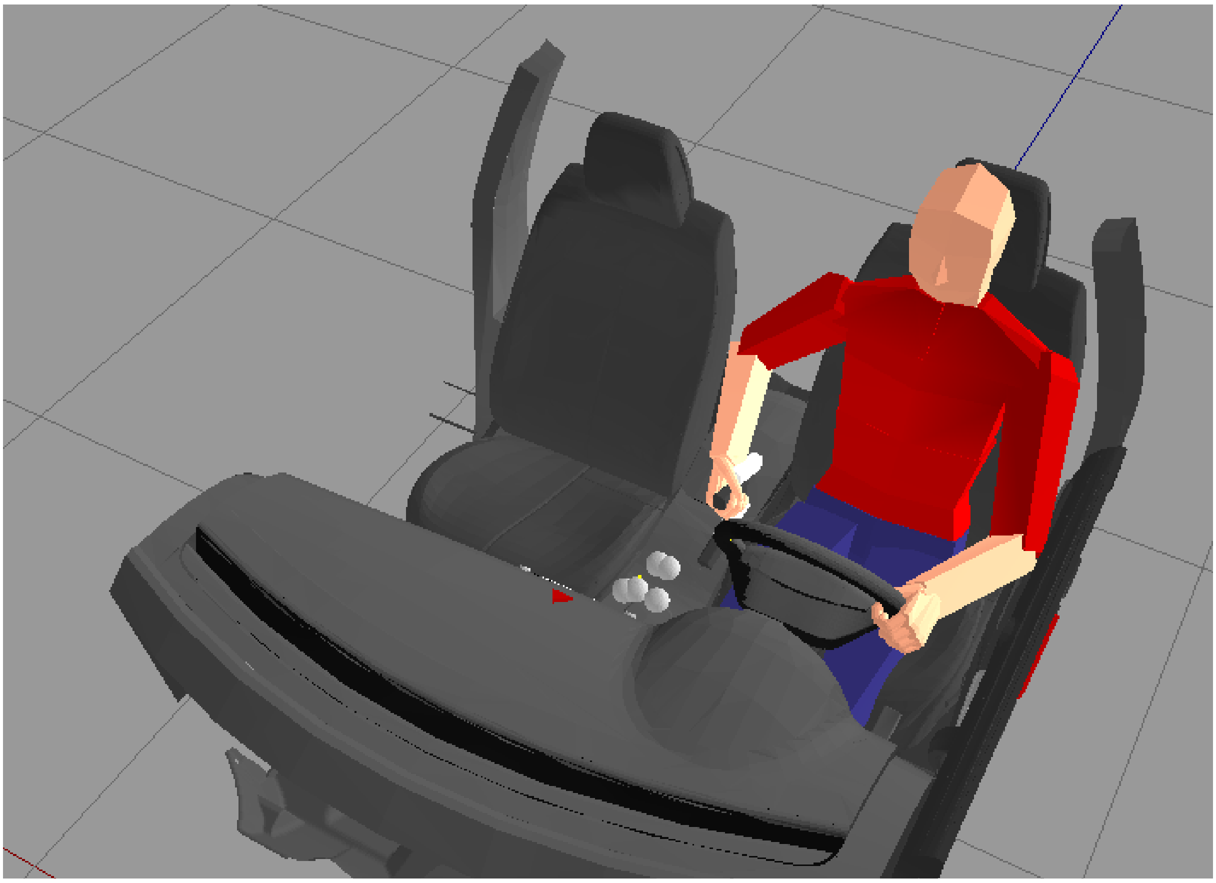

Figure 25: Initial (light grey) and adjusted position of the handbrake

The handbrake's position was perhaps the least user-friendly, as it negatively affected the predicted comfort of almost all drivers. It was positioned too far back, and so has been brought forward to adjust for this.

Figure 26: Initial (light grey) and adjusted position of the pedals

The pedals were the most exclusionary in their positioning, as everyone with a foot smaller than approximately 60th percentile Chinese female was unable to operate the accelerator with their heel on the ground. They also, less crucially, were too close to the left edge of the footwell. They have been moved right and down in the redesign.

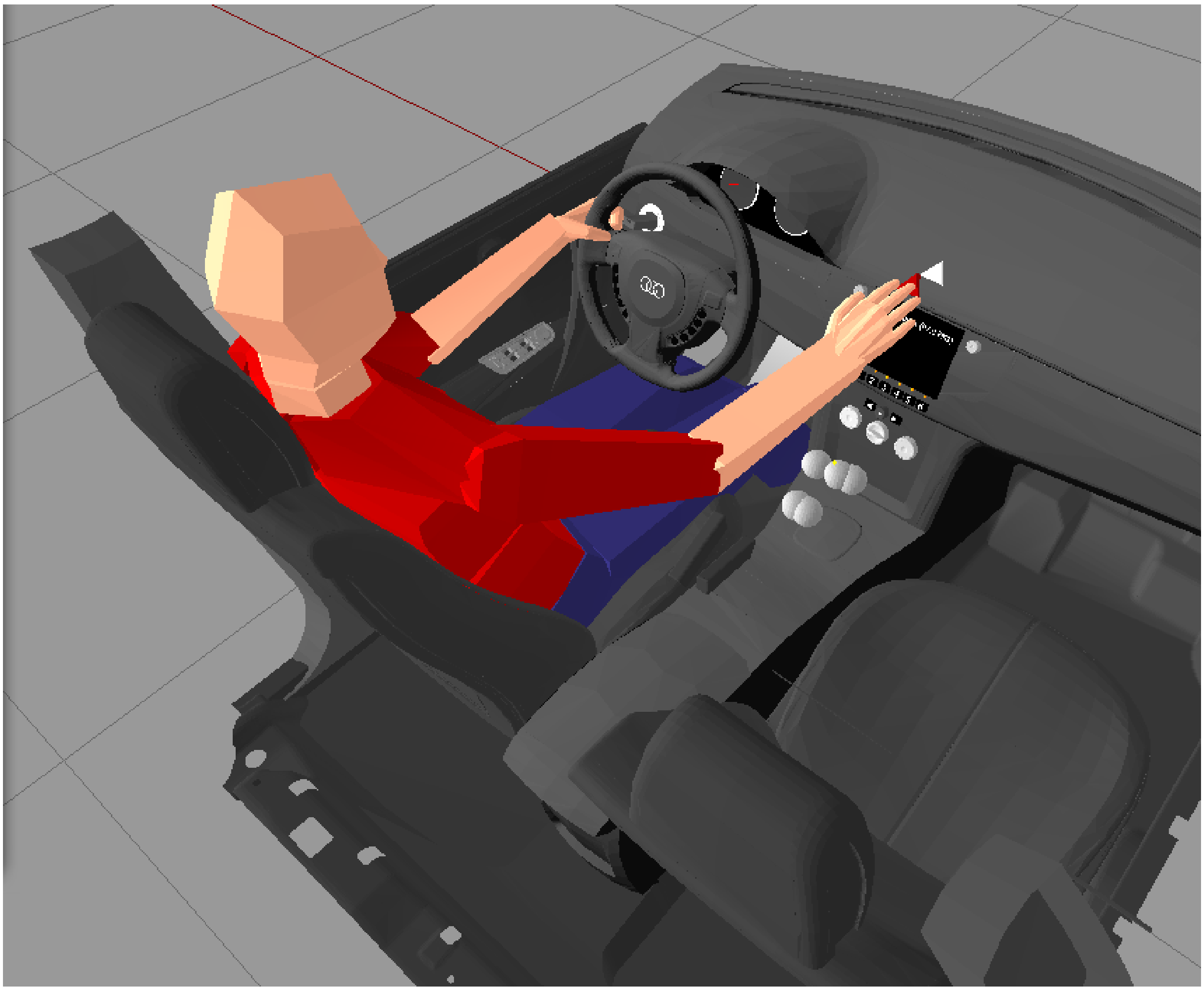

Figure 27: Initial (light grey) and adjusted position of the hazard light

The hazard light was adjusted slightly left and down to improve reach to it. This is a usability decision that could be overridden if design symmetry is considered more important.

Media Controls

Figure 28: Initial (light grey) and adjusted position of the media controls, volume is at the bottom.

Volume had a much higher location weighting than the frequency control, so at minimum these would be swapped. The redesign puts both of them on the same side of the touchscreen (Figure 28), maintaining the functional grouping and making the volume slightly easier to reach than the frequency. Both were also moved down for any extra reach distance that could be minimized.

The skip forward/backward buttons had higher weighting than the radio presets, and so swapping their positions (bringing along the central control dial) is recommended with the caveat that the functions of the touchscreen are unknown, and if the number keys are included, the principle of functional grouping may have precedence.

The volume and track skip functions could be additionally featured as buttons on the steering wheel.

HVAC

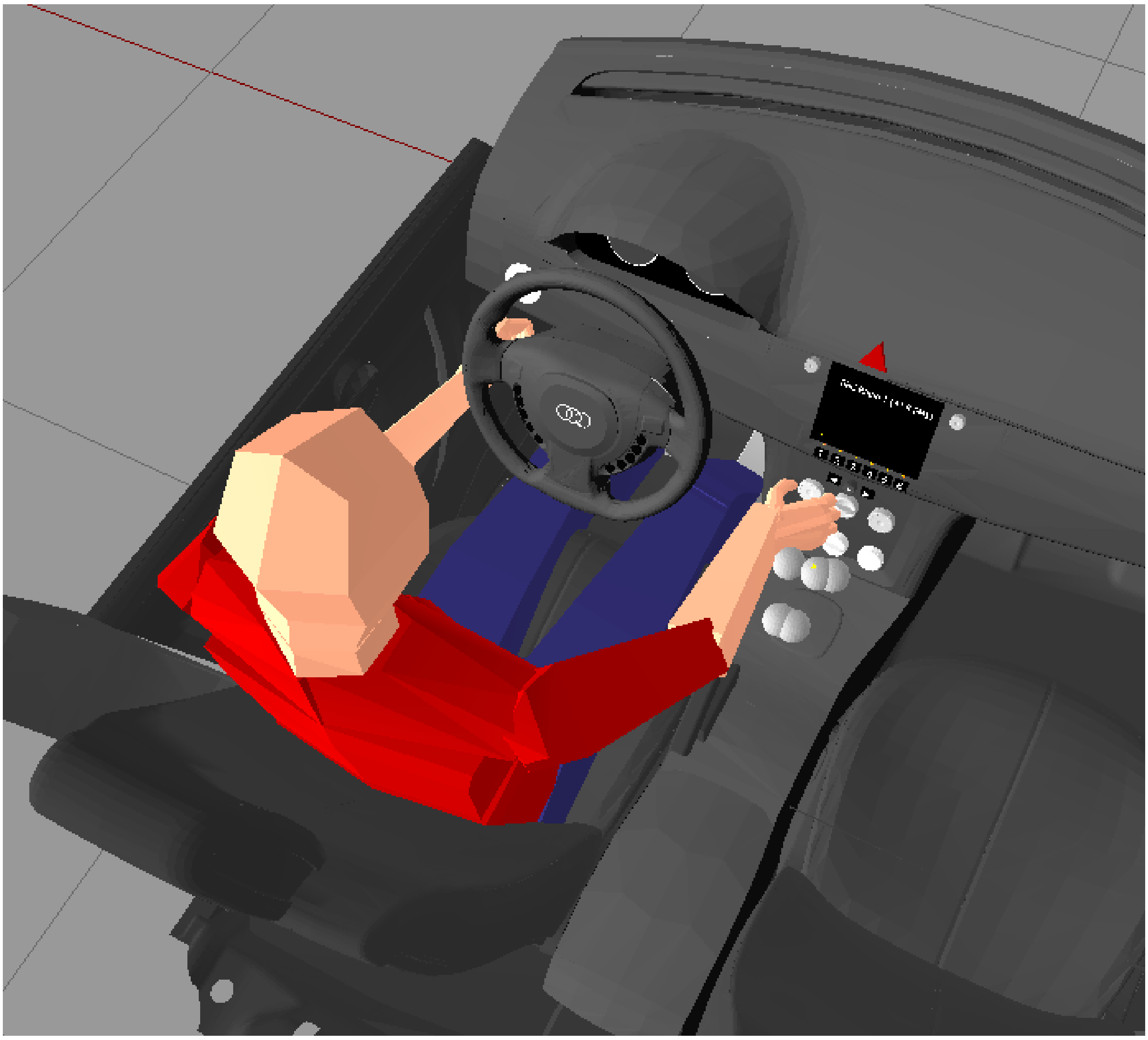

Figure 29: Initial (light grey) and adjusted position of the HVAC controls

The HVAC controls were also not in order of weighting, so this was changed to temperature, fan speed, airflow (left to right). The HVAC group was also moved up to be both closer and less obstructed by the gearstick.

Ignition

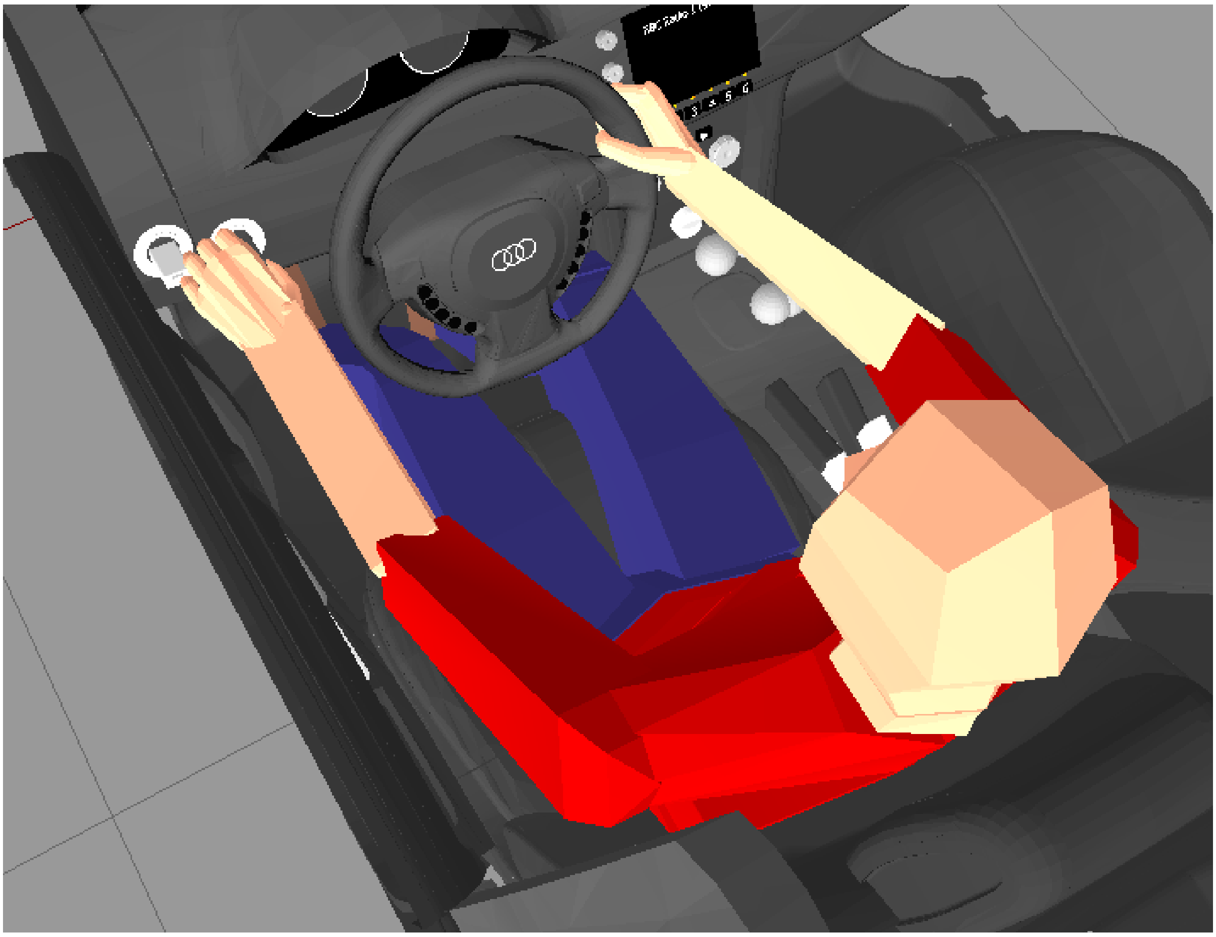

Figure 30: Ignition shifted right and down, rotated down slightly

The ignition required extra clearance from the door, and there was space to improve the ease of reach as well (Figure 30).

Window controls

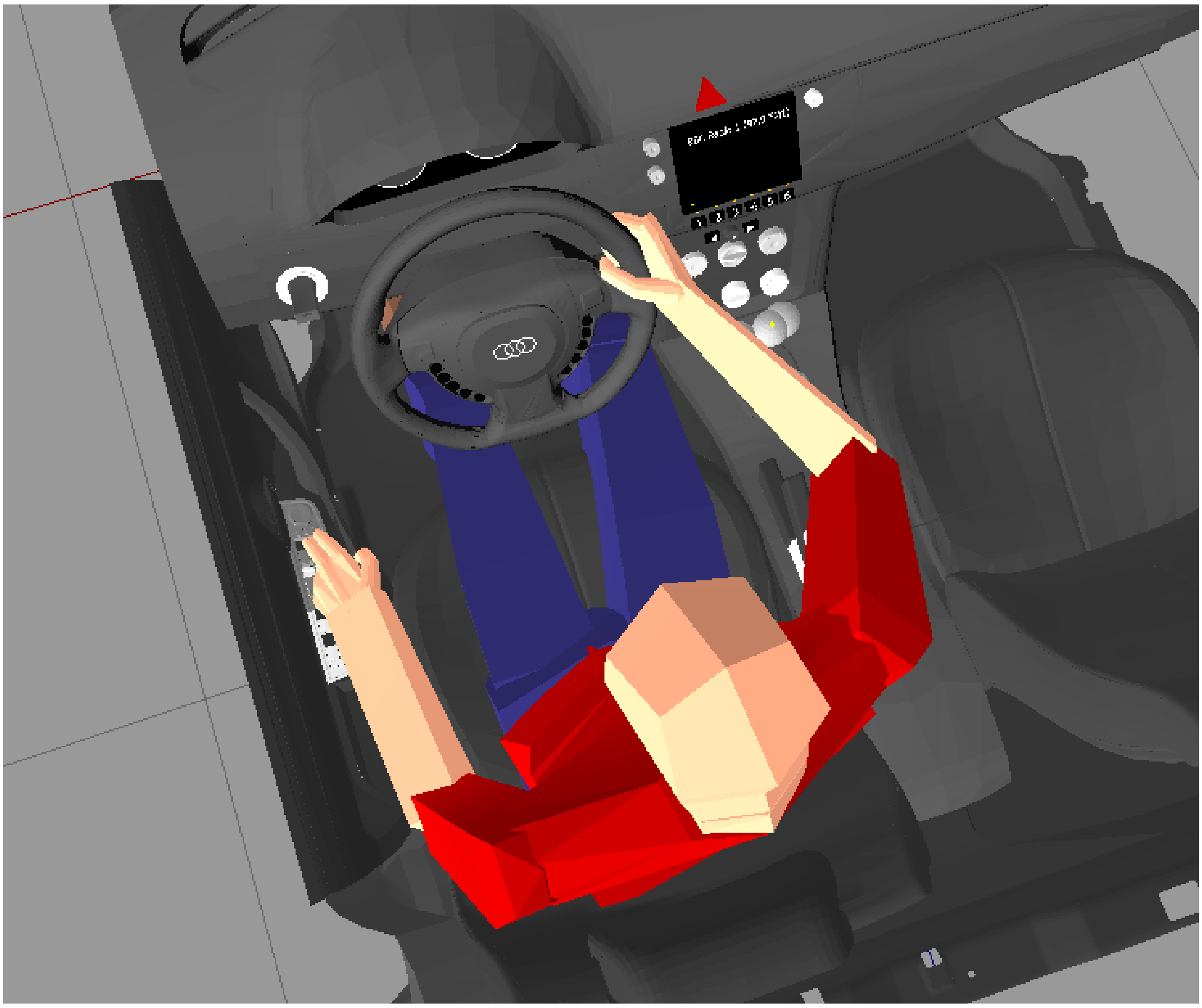

Figure 31: Initial (light grey) and adjusted position of the window controls

Window controls presented a clearance issue between the elbow/forearm and the door, so were moved as far forward as possible to compensate. The twist required to use the controls without clipping through the door is considerably less, making the comfort much less uncomfortable.

Steering wheel

The steering wheel should its maximum height increased. If it is too cost prohibitive to provide additional customization range, the whole range could be moved up.

Reach Validation

The reach distances in the redesign were compared against the initial design. As can be seen in Table 5, the changes make significant improvements to all the controls moved, making use easier and less dangerous.

Table 5: Improved reach distances with redesign (mm (change)) for each mannequin

Control	DM84	A8DM	A9DM	A11CF
Hazard light	4 (-20)	(now in reach)	(in reach)	(now in reach)
Ignition	(now in reach)	(in reach)	(in reach)	(in reach)
Temperature control	60 (-5)	74 (-16)	8 (-14)	23 (-27)
Volume	16 (-54)	15 (-69)	(now in reach)	(now in reach)
Frequency	24 (-6)	26(-11)	(now in reach	(in reach)

Summary

User research was carried out via observation, interview and questionnaire to better understand the task of driving. Anthropometric measurements and postures were recorded and recreated in SAMMIE to provide a real-world primary basis for suitable postures in car control evaluation. Using this and additional data in the literature, requirements were created. Chinese and Dutch datasets were chosen to fully span the range of sizes in European and Asian markets. Univariate analysis showed that the car would accommodate drivers between 60th percentile Chinese female (limited by accelerator height) and 84th percentile Dutch Male (limited by head clearance from the ceiling). Further analysis using the multivariate A-CADRE models (8 and 9 Dutch Male, 11 Chinese Female) was undertaken to find more problems with the positioning of controls. The positions of a number of controls were moved based on reach and vision, and was guided by 4 main principles including the frequency and importance of each control. The controls moved were the handbrake, pedals, hazard light, volume, frequency, window controls, ignition, and HVAC, decreasing reach distances, increasing available clearance and improving postural comfort.

Word Count: 3403/3500

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Appendix A: Information Sheet

Study of car control use and driver posture (coursework)

STUDY INFORMATION

Dear Participant

I am carrying out a research study for my coursework on the module DSC017 (Computer Aided Ergonomics) in Loughborough Design School, Loughborough University. The purpose of the study is to look at the controls used in a car, and the postures adopted by drivers. Your participation may consist of:

- Filling out a questionnaire.
- Individual interview, lasting approximately 10 minutes, which will be recorded for analysis.
- Observation of activities when driving normally, for a period of 2 journeys. The data will be recorded for analysis. All the information will be confidential and will be deleted after analysis
- Analysis of your posture while seated in a driving position in a stationary car. This will include measurement of joint angles as well as some of your limb lengths. Photos will be taken.

All references, quotes and images used in the coursework will be anonymous. All the information will be confidential and will be deleted after analysis.

If you want further information about the coursework, you can contact the module organisers, Russell Marshall (R.Marshall@lboro.ac.uk) and Steve Summerskill (s.j.summerskill2@lboro.ac.uk).

Yours faithfully,
Andrew Reece
a.z.m.reece-14@student.lboro.ac.uk

Appendix B: Consent form

Study of car control use and driver posture (coursework)

INFORMED CONSENT FORM

The purpose and details of this study have been explained to me. I understand that this study is designed to further scientific knowledge and that all procedures have been approved by the Loughborough University Ethical Approvals (Human Participants) Sub-Committee.

I have read and understood the information sheet and this consent form.

I have had an opportunity to ask questions about my participation.

I understand that I am under no obligation to take part in the study.

I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.

I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others.

I agree to participate in this study.

Your name ____

Your signature ____

Signature of investigator ____

Date ____

Appendix C: Observation results

Journey 1 (dry, daytime, 65 minutes)

Control	**Frequency**
Gearstick	>50 in 12mins
Handbrake	7
Volume	2
Frequency	2
Lights	4
Indicator	>50 in 53mins
GPS	3
Temperature control	3
Fan level	2
Ignition	4

Journey 2 (raining, nighttime, 60 minutes)

Control	**Frequency**
Handbrake	3
Volume	2
Lights	23
Windscreen wipers	11
Demister	2
Temperature control	5
Ignition	2

Appendix D: Questionnaire

Please ask for clarification if you are unsure what a question is asking for.

1) For how many years have you had a driving license? ________ *years*
2) How many models of car have you driven? ________ *models*
3) On average, how many days in a month would you drive? ________ *days*
4) How long is your typical journey when driving? _____ *hours* _____ *minutes*
5) Below is a list of car controls, please indicate your frequency of interaction with each, where an interaction requires you making an adjustment. Please also indicate the importance of the control and whether you consider it necessary to effectively drive a car. If there are any controls that have not been mentioned, please add them at the bottom.

Car **Control** in question	How frequently do you use the control? Where: **0 = Never** **1 = A few times per year** **2 = A few times per week** **3 = A few times per day/drive** **4 = A few times per 10 minutes** **5 = Multiple times per minute**	In terms of importance to you when driving, is this a **primary (1)**, **secondary (2)**, or **tertiary (3)** *control*?	Would you consider this control necessary in order to *effectively* drive a car? **(Yes/No)**
Steering Wheel	0 1 2 3 4 5		
Pedals	0 1 2 3 4 5		
Indicator	0 1 2 3 4 5		
Window Controls	0 1 2 3 4 5		
Ignition	0 1 2 3 4 5		
Gear Stick	0 1 2 3 4 5		
Horn	0 1 2 3 4 5		
Hazard light	0 1 2 3 4 5		
Handbrake	0 1 2 3 4 5		
Radio/MP3 Volume	0 1 2 3 4 5		
Radio Frequency	0 1 2 3 4 5		
Radio Presets	0 1 2 3 4 5		
Skip Forward	0 1 2 3 4 5		

Skip Back	0	1	2	3	4	5		
Seat angle adjust	0	1	2	3	4	5		
Seat location adjust (forward/back)	0	1	2	3	4	5		
GPS	0	1	2	3	4	5		
In-car computer control dial	0	1	2	3	4	5		
AC Temperature	0	1	2	3	4	5		
AC Airflow location	0	1	2	3	4	5		
AC Fan speed	0	1	2	3	4	5		
AC Outlet direction	0	1	2	3	4	5		
Overhead sun visor	0	1	2	3	4	5		
Seatbelt	0	1	2	3	4	5		
Internal Light	0	1	2	3	4	5		
External Lights	0	1	2	3	4	5		
Windscreen Wipers	0	1	2	3	4	5		
Odometer (Mile counter)	0	1	2	3	4	5		
	0	1	2	3	4	5		
	0	1	2	3	4	5		
	0	1	2	3	4	5		

Comments:

Appendix E: Questionnaire Results

Control	Frequency	Importance	Necessary	Location Weighting
Steering Wheel	5	1	1	100.0
Pedals	4.875	1	1	95.1
Indicator	3.9375	1.125	1	49.0
Window Controls	2.5	2.25	0	4.9
Ignition	2.625	1	0.875	27.6
Gear Stick	4.625	1	0.875	85.6
Horn	1.25	2.625	0.25	0.9
Hazard light	1.125	1.625	0.5	1.9
Handbrake	3.125	1.375	1	20.7
Radio/MP3 Volume	3.25	2.75	0	5.6
Radio Frequency	1.5	2.75	0	1.2
Radio Presets	1.125	2.875	0	0.6
Skip Forward	1.75	3	0	1.4
Skip Back	1.625	3	0	1.2
Seat angle adjust	1.5	1.375	1	4.8
Seat location adjust (forward/back)	1.75	1.25	1	7.8
GPS	1.5	2.5	0.25	1.4
In-car computer control dial	0.625	2.714285714	0.125	0.2
AC Temperature	2.125	2.25	0.375	3.6
AC Airflow location	1.5	2.5	0.125	1.4
AC Fan speed	1.75	2.5	0.125	2.0
AC Outlet direction	1.625	2.5	0.125	1.7
Overhead sun visor	1.875	2.125	0.5	3.1
Seatbelt	2.875	1.125	0.875	26.1
Internal Light	1.875	2.375	0.125	2.5
External Lights	2.875	1.25	1	21.2
Windscreen Wipers	2.375	1.125	1	17.8
Odometer (trip counter)	0.75	2.75	0	0.3

Appendix F: Hierarchical task analysis

Super-ordinate number	Goal	
	Plan	
	Operations	Notes
0)	**Drive a car**	
	Plan: 1, then 2-9 as conditions dictate, then 10	
	1) Start up the car	
	2) Pull away from stopped	
	3) Follow road	
	4) Turn at a junction	
	5) Adjust for weather conditions	
	6) Adjust comfort	
	7) Adjust entertainment	
	8) Control GPS	
	9) Bring car to a stop	
	10) Shut down the car	
1)	**Start up the car**	
	Plan: optionally 1, (2 then 3), 4, optionally 5, in any order	
	1) Adjust the seat	
	2) Put key in ignition	Ignition
	3) Turn key	
	4) Put on seatbelt	
	5) Reset trip counter (odometer)	

2)	**Pull away from stopped**	
	Plan: 1 then 2 then 3 then 4 then 5 then 6	
	1) Depress clutch	
	2) Put car into first gear	Gearstick
	3) Check mirrors	
	4) Depress accelerator	Pedals
	5) Lower handbrake	Handbrake
	6) Raise clutch	Pedals
3)	**Follow road**	
	Plan: 1, 2 and 3 in parallel	
	1) Monitor conditions on road	
	2) Monitor car status	
	3) Adjust speed	Pedals
	4) Adjust direction	Steering wheel
3.1)	Monitor conditions on road	
	Plan: 1 then 2, 3 if hazard spotted	
	1) Look ahead	Both close and far distance
	2) Check mirrors	
	3) Press hazard light	
3.2)	Monitor car status	
	Plan: 1, 2 or 3, sporadically	
	1) Check current speed	Frequently "Once every 3 or 4 seconds"
	2) Check fuel level	
	3) Check rev-meter	

4)	**Turn at a junction**	
	Plan: 1 then 2 then 3 then 4	
	1) Check mirrors	
	2) Indicate turning direction	Indicator
	3) Adjust speed	Pedal
	4) Turn car	Steering wheel
5)	**Adjust for weather conditions**	
	Plan: 1 or 2 or 3, as appropriate	
	1) Control lights	
	2) Control windscreen wipers	
	3) Adjust overhead sun visor	
6)	**Adjust comfort**	
	Plan: 1 and/or 2 and/or 3	
	1) Control Heating	
	2) Press demister button	
	3) Consume food/drink	
6.1)	**Control Heating**	
	Plan: 1 and/or 2 and/or 3 in any order	
	1) Adjust air vent direction	
	2) Adjust flow control	
	3) Adjust temperature dial	
7)	**Adjust entertainment**	
	Plan: 1 and/or 2	
	1) Control volume	
	2) Change audio content	

7.2)	**Change audio content**	
	Plan: 1 and/or 2 or 3 or 4	
	1) Control Frequency	
	2) Choose Radio preset	
	3) Skip track forward	
	4) Skip track backward	
9)	**Bring car to a stop**	
	Plan: 1 then 2 then 3 then 4 then 5	
	1) Check mirrors	
	2) Depress brake	
	3) Depress clutch	
	4) Change gear to neutral	
	5) Raise handbrake	
10)	**Shut down the car**	
	Plan: 1 then 2 then 3	
	1) Take off seatbelt	
	2) Turn key	
	3) Remove key from ignition	

Appendix G: Participant Anthropometrics

P	Age	Sex	Stature	Sit Height	B-K length	Sit Acr. height	Knee height	Arm L	Hand L	Shoulder br
			mm %ile	mm %ile	mm %ile	mm %ile	mm %ile	mm %ile	mm %ile	mm %ile
1	18	M	1600	847	540	560	476	657	192	409
			1.32	2.22	1.34	7.59	0.8	0.01	58.79	45.03
2	22	M	1915	985	644	642	598	849	220	450
			98.89	96.25	86.41	78.85	97.04	93.88	99.89	96.19
3	19	M								
4	21	M	1732	928	598	602	506	694	185	420
			37.05	58.48	35.71	38.64	8.82	0.25	31.39	64.96
5	23	F	1522	846	566	507	455	648	171	378
			6.4	36.26	1.48	28.82	7.11	3.99	34	76.27
6	18	F	1651	894	587	608	529	707	172	376
			68.48	86.5	68.21	67.93	90.73	41.18	37.86	72.54
7	51	M	1702	862	610	585	527	763	184	662
			22.37	5.49	50.64	22.6	27	19.19	27.9	99.01

Table showing participant anthropometrics in mm and UK percentile of their gender.

Appendix H: A-CADRE

Manikin	Stature	Sitting Height	Popliteal	Buttock -Knee	Hand Length	Arm	Acrom. Ht. Sit	Biacromia l Breadth	Range	Std Dev
8	38.3	83.2	10.6	33.1	24.3	19.1	84.9	79.4	74.3	30.898
9	61.7	16.8	89.4	66.9	75.7	80.9	15.1	20.6	74.3	30.898
7	24.4	21.6	37.7	43.5	76.6	59.4	20.1	90.4	70.3	26.433
10	75.6	78.4	62.3	56.5	23.4	40.6	79.9	9.6	70.3	26.433
6	52	85	59	16.3	80.1	51.9	77.3	50	68.7	22.232
11	48	15	41	83.7	19.9	48.1	22.7	50	68.7	22.232
3	82.7	31.5	91.8	95.7	90.6	95.3	35.8	88.3	64.2	26.764
13	17.3	68.5	8.2	4.3	9.4	4.7	64.2	11.7	64.2	26.764
4	95.4	91	97.3	81.6	92.5	93	88.9	45.6	51.7	16.866
14	4.6	9	2.7	18.4	7.5	7	11.1	54.4	51.7	16.866
2	91	89.7	67.5	92.6	45.9	71.1	93.4	76	47.5	16.678
12	9	10.3	32.5	7.4	54.1	28.9	6.6	24	47.5	16.678
5	75.6	93.6	64.4	61.8	92.9	80	92.2	97.8	36	13.985
15	24.4	6.4	35.6	38.2	7.1	20	7.8	2.2	36	13.985
1	99	96.6	98.1	98.6	98	98.8	97.1	97.1	2.4	0.889
16	1	3.4	1.9	1.4	2	1.2	2.9	2.9	2.4	0.889
17	50	50	50	50	50	50	50	50	0	0.000

Dimensions are given in percentiles