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An approach to vehicle design: In-depth audit to understand the needs of older drivers

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ABSTRACT

The population of older people continues to increase around the world, and this trend is expected to continue; the population of older drivers is increasing accordingly. January 2012 figures from the DVLA in the UK stated that there were more than 15 million drivers aged over 60; more than 1 million drivers were aged over 80. There is a need for specific research tools to understand and capture how all users interact with features in the vehicle cabin e.g. controls and tasks, including the specific needs of the increasingly older driving population. This paper describes an in-depth audit that was conducted to understand how design of the vehicle cabin impacts on comfort, posture, usability, health and wellbeing in older drivers. The sample involved 47 drivers (38% female, 62% male). The age distribution was: 50–64 (n = 12), 65–79 (n = 20), and those 80 and over (n = 15). The methodology included tools to capture user experience in the vehicle cabin and functional performance tests relevant to specific driving tasks. It is shown that drivers' physical capabilities reduce with age and that there are associated difficulties in setting up an optimal driving position such that some controls cannot be operated as intended, and many adapt their driving cabins. The cabin set-up process consistently began with setting up the seat and finished with operation of the seat belt.

1. Introduction

There is a growing older population globally: in Europe the percentage of people aged over 65 is expected to rise from 16% in 2010 to 29% in 2060 (Creighton, 2014). The European population aged over 80 is set to rise significantly; in 1960 it was just 1–2%, but in 2010 this figure reached 4%, and it is estimated that in Europe the population aged over 80 will increase to 12% by 2060. In parallel to this, the number of older drivers is increasing across the world. According to January 2012 figures of the DVLA in the UK, there are more than 15 million drivers aged over 60; more than 1 million are aged over 80 (Institute of Advanced Motorists, 2012; Dvla, 2010). Drivers aged 65 and older are predicted to represent over 16% of the driving population in the USA by 2020 (Tamiya et al., 2011). It has been estimated that 11% of over 65s buy a new car every two years (Statista, 2016). The automotive industry is therefore facing new challenges as the market demographic evolves (Bhise, 2012). One challenge is determining and meeting the needs of older drivers, which represents and increasingly important target population. Driving is an assumed activity for many older people whilst carrying out their daily activities and vital for maintaining independence in tasks such as shopping, keeping medical appointments, performing voluntary duties, sustaining a contributory role in the family, and maintaining a social life (e.g. Musselwhite and Haddad, 2008). In a questionnaire study of over 900 respondents, Karali et al. (2016) found that older drivers (65+) reported more discomfort in the lower limb when driving than younger drivers, although back discomfort reduced. A higher prevalence of older drivers than younger drivers reported driving in challenging conditions such as foggy days or busy traffic 'difficult'; similarly more older than younger drivers found it difficult to move their body when reversing (28% vs 22%). It was noted that about 10% drivers of all ages found adjusting the seat controls difficult.

The literature indicates that many of the issues for older drivers identified in the 1990s relating to visual, cognitive, environmental and particularly physical factors are still commonly encountered (Middleton et al., 2005; Bradley et al., 2008; Musselwhite and Haddad, 2008; Smith et al., 1993). According to Gyi (2013) more

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data is needed to focus on dynamic and functional anthropometric measurements in vehicle design to accommodate the specific needs of older drivers. Examples include postures for reversing, postures for operation of seat adjustment controls, opening car boots, reach to the seat belts and reach to adjust mirrors. A study conducted by Williams et al. (2011) explored user-centred design and evaluation of electrically operated seat adjustment controls in luxury vehicles (SUVs). This study was based on analysis of the positive and negative comments on ease of use, accessibility and feel. Negative comments were mainly related to obstruction and space restrictions when accessing the controls on the side of the seat, i.e. the arm rest was causing obstruction. Interestingly, this study did not focus on age and gender. Furthermore, the minority of vehicles are equipped with electrically operated seat controls and manual adjusters have additional design challenges.

Kyung and Nussbaum (2010) compared the postures of older drivers (n = 20) with younger (n = 38) in two different vehicle classes: sedan and SUV. They identified that older drivers had a smaller angle of the right elbow and the left hip in the sedan. The results for SUVs identified six joint angles that were smaller; indicating older drivers adopted postures close to the steering wheel. Differences between males and females were not explored in this study. Similarly, a study conducted by Porter and Gyi (1998) identified that females had lower arm flexion and elbow angles compared to males; this also indicates that females adopt their driving postures closer to steering wheel compared to males, but this study did not compare ages. Interestingly, the results of a questionnaire survey study conducted by Herriotts (2005) revealed that 95.2% of drivers were able to adopt a comfortable driving position. Whilst 31% of older drivers reported using additional items on their seat such as a bead mat and seat cushion, only 2.1% of younger drivers did. The study was based on a postal survey, to explore difficulties experienced by older drivers with an aim to identify specific focus areas for further research. The sample was formed of a large group of older drivers (n = 1013, age 60–79) and a small group of younger drivers (n = 97, age 20–59).

While not a focus for this study, cognitive and physiological decrements would be expected to affect driving performance for older drivers. Musselwhite (2016) summarised the issues facing older drivers in 7 categories: attention, cognitive overload, cognitive processing speed, perceptual speed, working memory, task switching and eyesight. These were mapped on to common driving errors and it was noted that many of the categories of decrement would be expected to directly affect all of the errors in the list. The cognitive and physiological capabilities of older drivers should not be assumed to be identical to those of younger drivers, and will become more important to manufacturers as the number of older drivers increases. However the cognitive performance of all ages has a wide range, and many older drivers can perform very well in tests. For example, Key et al. (2016) showed that situation awareness scores for older individuals often matched and exceeded those for younger ones, although on average younger drivers showed superior hazard perception.

Designing vehicles to accommodate the needs of older drivers has social and economic implications for users and the manufacturers. Identifying these needs will enable drivers of all ages to be better accommodated in the design process; older users can maintain their independence, drive for longer periods and remain socially connected for longer. In return this would have a positive impact on their health and reduce the workload of daily activities e.g. shopping, visiting doctors and relatives etc. In parallel to this, manufacturers would potentially increase their sales to this market with constant improvements to their vehicles and technologies. Whilst manufacturers do aim to be inclusive in their designs, it is recognised that there is an increasing population of older drivers and future improvements need to ensure that the entire market is considered. The aim of the research presented in this paper is to understand how design of the vehicle cabin impacts on older drivers. To this end, a methodology is also described which may be of interest to other researchers in the automotive field.

1.1. Purpose/objectives of the study

The purpose of this study was to explore how users (older drivers) interact with controls in automotive cabins. It was designed to capture the user experience in relation to design of the vehicle cabin (e.g. seat set-up process, the seat design, ease of adjustments, posture analysis), to measure physical functional performance of older drivers and understand how these can affect driving related tasks; cognitive function was out of scope for this study. The focus of the study was directed by the outcomes of a previous questionnaire of over 900 drivers with 420 aged 65 or over (Karali et al., 2016).

2. Methodology

Two vehicles were audited in the same session: the participant's own vehicle and a test vehicle (2010 Nissan Qashqai sports utility vehicle, 2010–2013 model variant (SUV)) which was the same for each person. A repeated measures design was used to understand the problems experienced, preferences, and likes/dislikes about the vehicle cabin area such as the seat and seat controls. The detailed procedure is summarised in Table 1. The audit was conducted for convenience either at the participant's home, Loughborough University or other suitable venue and was designed to last between 1.5 and 2 h. Assessment tools were selected from Eby et al., (2006) in order to understand how declines in functional performance could affect carrying out specific driving related tasks (shown in Table 2). These tests were included in order to determine whether specific physical performance limitations affected the overall driver abilities. The Hamilton Veale test was used for the assessment of contrast sensitivity.

At the start of the audit background information was obtained about participants (e.g. gender, age). The audit was carried out first in the participant's own vehicle (a familiar vehicle) and then the test vehicle (an unfamiliar vehicle). The participant's vehicle was used first in order to help build rapport between experimenter and the volunteers, and to allow them to learn the test protocol in a familiar environment. The seat set-up process was evaluated to capture user decisions on seat and driving positions and their experiences of conducting specific tasks to achieve these decisions. Both qualitative and quantitative data were obtained from video recordings using a rearward-facing wide-angle camera mounted on the windscreen. Assistance was given (by the researcher) to participants who struggled or needed help during the seat set-up process (e.g. locating and operating the controls) and this was noted. A 5-point scale was used for the usability evaluation of the controls reach (too far, slightly too far, ok, slightly too close, too close), ease of operation and accessibility (very easy, easy, ok, difficult, very difficult). Posture was measured following Porter and Gyi (1998) to capture the driving position of participants. Posture measurements were taken with an extendable goniometer (Fig. 1) to measure the joint angles (based on anatomical landmarks) and seat positions measured using a specially designed tool (Fig. 2). Finally, the functional assessments (Table 2) were taken of participants, together with anthropometric measurements using methods described in Pheasant and Haslegrave (2006).

A stratified purposive sampling strategy was adopted focusing on age. Males and females were sought to participate in the study. The sample was divided into three age sub groups (50–64, 65–79

Table 1
Detailed procedure of the study.

Sections	Procedure and questions
Background questions	Year of birth? Gender? Occupation (working, retired, semi-retired)
Own/familiar vehicle questions	Make? Model? Annual mileage? Years driving licence held?
Seat set-up process	The procedure started with their own vehicle followed by the test vehicle. A wide angle camera was mounted facing the driver on the windscreen to record the seat set-up procedure. The driver's seat position was standardised – rear most, lower most and reclined (110–150°). Participants were given instructions before getting into their vehicle to carry out the tasks to adopt a comfortable driving position. Video of each participant was taken and played back to them: they were then asked to talk through their decisions and actions. Data included: a breakdown of the task; the sequence (order) of the seat set-up task; time taken to operate each control e.g. seat lifter, lumbar support and the total time (seconds) to set-up their seat.
Posture analysis	Driving postures captured in both vehicles (measurements and photographic images). Measurements: trunk-thigh angle, arm flexion, knee angle, ankle angle, neck inclination and elbow angle. Seat positions measured were: min/max positions together with the adopted position by participants of seat fore/aft and seat height.
Usability evaluation	Evaluation of seat controls in both vehicles i.e. reach, ease of operation and accessibility. Seat controls evaluated were: seat recliner, seat lifter, lumbar support adjustment, head rest and fore/aft adjustments using 5 point scales (very easy – very difficult)
Anthropometric data	Measurements: stature, sitting height, knee height, sitting hip width and popliteal length.

Table 2
Specific assessment tools in literature used to asses older drivers-adapted from Eby et al. (2006).

Author	Type	Assessment	Method
Haymes and Chen (2004)	Pelli-Robson contrast sensitivity	Contrast sensitivity	Assessment of how well large faint objects are seen. Conducted through standardised conditions. Uniformly large letters which reduce in contrast (fade out) as the test progresses. The subject reads as many as possible from 1 m distance. The score is the faintest triplet that for which 2 of the 3 letters are correctly identified.
Charlton et al. (2002)	Clock reading test	Upper body flexibility and range of motion	Conducted under standardised conditions by measuring the ability of the subject to look over their shoulder. The subject sits in a standard (non-swivel) chair. The researcher stands 3 m directly behind holding a clock with hands set to 3.00 or 9.00. The score is pass/fail for correct reading of the clock.
Smith et al. (2000)	9-hole peg test	Hand coordination and dexterity	The task requires subjects to place the pegs into a peg board one at a time and then remove them. It is conducted with dominant and non-dominant hand and the score is the time taken to complete the tasks.
Charlton et al. (2002)	Arm reach test	Shoulder flexibility	The subject remains seated facing the researcher and is then asked to raise his/her right arm and then down again. The same process is carried out with the left arm. The score is pass or fail: if their elbow cannot be raised above shoulder height then it is a fail.
Marottoli and Richardson (1998)	Confidence scale	Assessing confidence on specific driving tasks	Self-rated confidence with a scale from 0 (not confident at all) to 10 (completely confident). The driver rates his/her self on their experience with 10 driving conditions. These include driving at night, driving in bad weather and parallel parking.

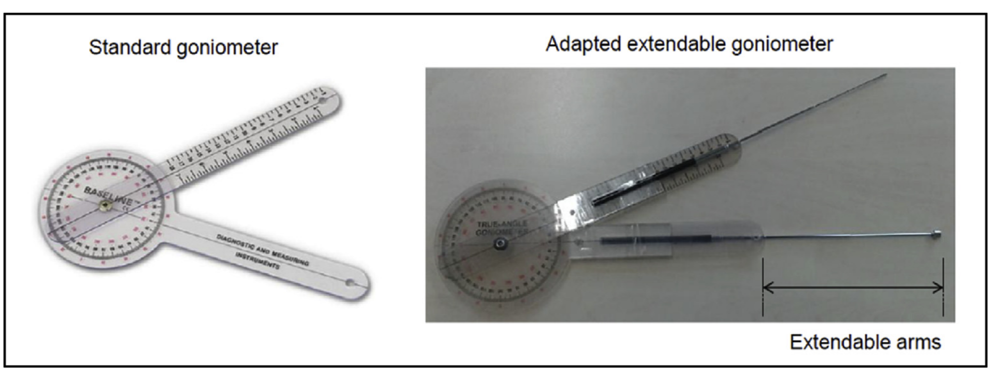

Fig. 1. Extendable goniometer used for assessing joint angles.

and over 80s) to allow comparisons. Various organisations were approached during the recruitment process including U3A (University of Third Age), Probus and IAM (Institute of Advanced Motoring). A total of 47 older drivers (38% female, 62% male) participated; thus there were more male participants volunteering than female. The age distribution was: 50–64 (n = 12; 5 m/7f), 65–79 (n = 20; 14 m/6f) and 80 and over (n = 15; 10 m/5f).

Approval was obtained from the Loughborough University Ethical Committee in April 2013. A detailed participant information sheet was prepared for participants to read and understand the details of the study. After reading the information sheet an informed consent form was given to each participant for them to sign and agree to take part.

3. Results

It was found that participants' mileage was highest for the youngest group (mean: 9125), and lowest for the oldest group (mean: 5167). The 65–79 group had a mean mileage of 7075. The oldest car was model year 1999; the newest 2013. Vehicle makes comprised Audi (1), BMW (3), Citroen (3), Fiat (1), Ford (3), Honda (3), Jaguar (2), Mazda (3), Mercedes (2), Mini (2), Nissan (1),

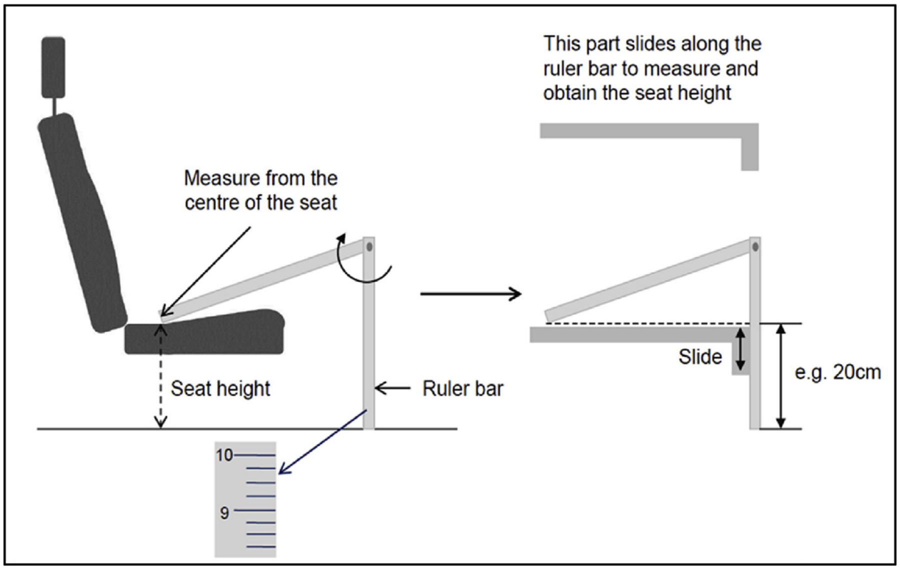

Fig. 2. Seat height measurement tool. The articulating hinge is locked when the seat height has been measured. The tool is removed from the vehicle and the seat height read from the ruler bar scale using the slide.

Peugeot (4), Renault (2), Rover (2), Skoda (1), Toyota (6), Vauxhall (3), Volvo (1), and VW (4).

3.1. Seat set-up process (observations)

It was observed that the majority (60%) of older females (over 80s) and 17% of those aged 65–79 had made design modifications to their own vehicle. These included seat pads to increase the seat height (for females under 155 cm), a foot rest for the left foot, cushions underneath the thighs to extend cushion length and a shopping bag to reduce seat cushion friction and help swivel their body during ingress/egress (Fig. 3).

From the images in the video analysis (Fig. 4), the majority of participants (all age groups) had difficulty with adjusting the head rest height in both vehicles. Many (approximately 40%) also had difficulty turning their head and body around to reach and operate the headrest; the majority of these were in the over 80s cohort. Difficulties were also experienced with finding and pressing the button to operate the head rest in both vehicles. Most participants had difficulty finding/locating specific seat controls such as the seat recliner, lumbar support adjustment and steering wheel adjustment in both the familiar and unfamiliar vehicles. Some also had

Fig. 3. Use of additional items and design modifications made to the seat.

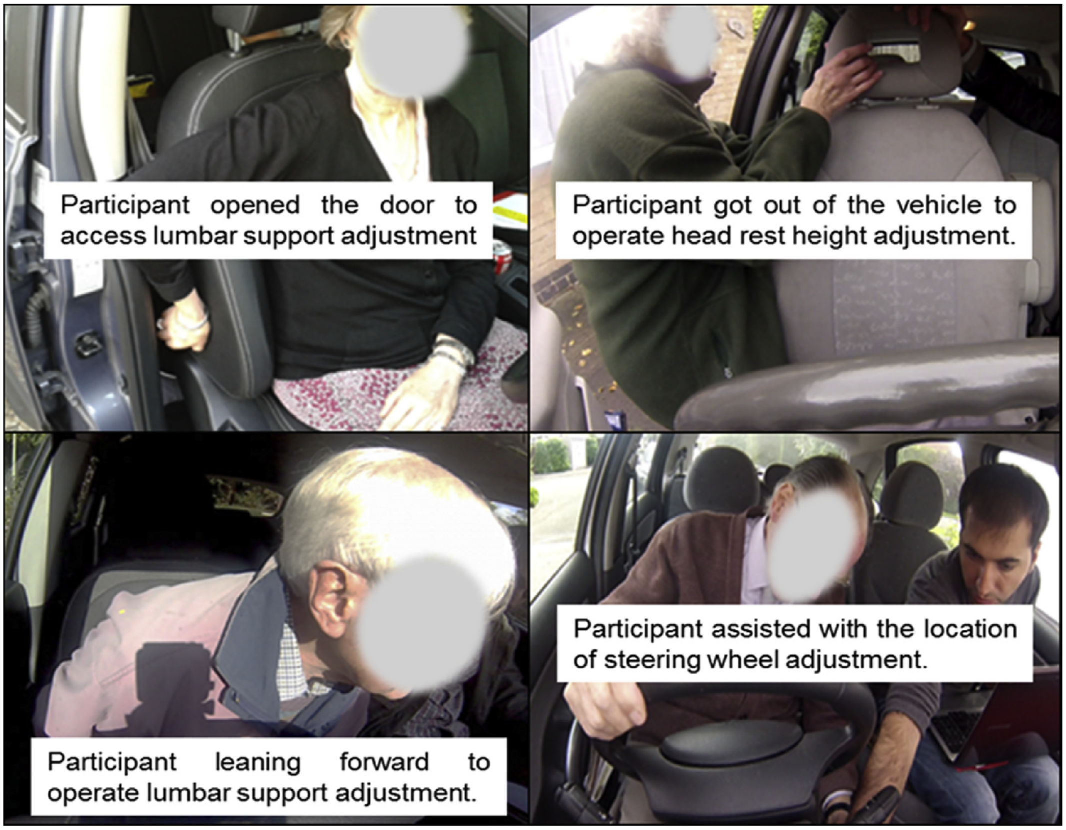

Fig. 4. Still images from video observations: difficulties with reaching, accessing, finding and operating controls.

difficulty accessing the lumbar support adjustment and the seat recliner; they frequently had to open the door in order to have enough space for hand/arm movements during operation. In the test vehicle, approximately 25% of participants needed to lean forward in order to operate the lumbar support adjustment; in this position their back was not resting against the seat and they reported that, as a result, they did not receive any feedback during operation.

There were also items that were reported to be acceptable by participants. Participants particularly those with short stature (under 1.55 cm) were satisfied with the seat height adjustment range of the test vehicle as they were able to obtain a good field of view and felt confident. The over 80s reported getting into and out of the test vehicle was easier than their own vehicle as the seat was located at a higher level and less effort was needed; this may be true of other SUVs with a similar driving position. The lumbar support adjustment in the test vehicle was also reported as pleasant due to its design; "it has a rubber texture easy to grip with a soft feel and rotates smoothly". The test vehicle was new and therefore had minimal wear-and-tear, unlike many of the participants' vehicles which were older. It was observed that in general the seat lifter and fore/aft controls were easy to locate and operate in both vehicles.

3.2. Seat set-up process (video analysis)

The videos recorded for each participant in both vehicles were analysed and coded in order to extract a breakdown of the tasks, the order of the seat set-up task, time spent on each control and total time to set-up their seat. Each control used during the set-up process was given a number from 1 to 8 (i.e. seat fore/aft adjustment = 1, seat height adjustment = 2 etc.). It is important to note that some participants did not have all these features in their own vehicle e.g. steering wheel/lumbar support adjustment.

The seat setup process was coded such that all data was on a normalised scale. Therefore, it allows for controls that were adjusted at the beginning of the process to be assigned a low score and the controls adjusted at the end of the process to be assigned a higher score. The method scores the first adjustment at '0%' through the process and the last adjustment at '100%' through the process and intermediate steps assigned equally spaced. For example if a participant carried out 5 tasks in total; this is then divided by 100 and equally distributed for each task, starting from 0 and increased by a value of 25 for each task, ending with the value 100 for the final task. If a participant conducted the set up process in the following order: seat height adjustment (control 2), seat recline (control 3), seat fore/aft (control 1), head rest height (control 4) and seat belt (control 5), data was coded to give seat height adjustment a score of 0, seat recline 25, seat fore/aft 50, head rest height 75 and seat belt 100. If a control was used more than once it could be scored twice. This process was completed for the whole sample (for both vehicles), and the median and quartile values were obtained. Table 3 shows these values in the order they were operated by the whole sample in both vehicles. For example, the seat fore/aft adjustment had the smallest median value in their own vehicle, which indicates that this control was operated at the beginning of the set-up process. The seat belt had the largest median value indicating that it was operated as the last step of the set-up process in their own vehicle.

The order of the tasks carried out in both vehicles separately for the whole sample was analysed using a Wilcoxon-signed rank test by comparing all 8 controls against each other through a matrix

Table 3
Median and quartiles for both vehicles (the order of the tasks carried out by whole sample; sorted by median order in own vehicle).

Seat controls		Own vehicle			Test vehicle		
Control type	Control number	25% ile	Median	75% ile	25% ile	Median	75% ile
Seat fore/aft	1	0	22.5	38	0	17	40
Seat recline	3	17	33	50	13	20	41
Seat height	2	18	40	65	16	25	33
Lumbar support	5	40	50	86	66	67	80
Steering wheel	6	29	53	80	40	50	64
Other	8	44	61	83	42	60	100
Head rest height	4	50	66	75	67	80	83
Seat belt	7	100	100	100	100	100	100

table in participants own vehicle and in the test vehicle (Table 4).

Based on the median values obtained (Table 3) and the results (*p* values), obtained through Wilcoxon signed-ranked test (Table 4), it is possible to understand the order of the controls operated during the seat set-up process for both vehicles. If there was a significant difference between control scores they occurred in a consistent order in the sequence. Seat height, recline and fore-and-aft were consistently adjusted early in the sequence; seat belt was adjusted at the end (Fig. 5).

3.3. Posture analysis

The posture angles of each participant were obtained after setting up each car seat in a comfortable driving position. Age and gender differences were explored and an ANOVA test was conducted in order to explore statistical significance. Only an increase in neck inclination ($p < 0.05$) was identified with increasing age; this was for both vehicles. In terms of gender (Table 5), significant differences were found between males and females for trunk-thigh angle (test vehicle only), arm flexion (both vehicles) and elbow angle (both vehicles) with the test vehicle.

3.4. Seat and seat controls evaluation

Participants were asked to evaluate the seat controls of both vehicles. Combined results for the whole sample are shown in Table 6 for their own vehicle and test vehicle (familiar + unfamiliar). A high proportion (41%) of participants reported the reach distance (reach) of the head rest control as 'too far away' in their own vehicle. Additionally, 37% reported the reach distance for the lumbar support as either 'too close' (16%) or 'too far' (21%). The head rest (50%), lumbar support (37%) and seat recliner (34%) controls were also frequently reported as being more difficult to access (hand/arm access). The head rest control (66%) and the lumbar support adjustment (42%) were more frequently reported as difficult to operate. In addition, difficulties were found with the seat recliner (26%) and seat lifter controls (25%).

With the test vehicle, the head rest and lumbar support controls were more frequently reported as being 'too far away' (38% and 34% respectively). The lumbar support (75%), head rest (66%), and seat recliner (36%) were more frequently reported as difficult to access (hand/arm access). In addition, 87% of participants reported experiencing difficulty with the operation of the head rest height control, and 23% reported difficulty operating the lumbar support adjustment. Age and gender were compared. No significances were found for gender. However, more difficulty was reported by older individuals with operating the head rest height adjustment for older drivers compared to younger drivers ($p < 0.05$).

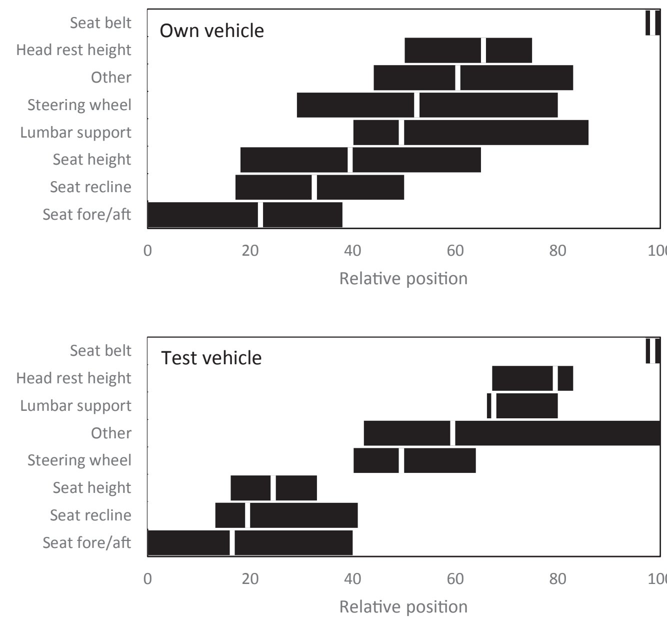

Fig. 5. Median (white bar) and quartile ranges for relative position in adjustment sequence for participants' own (top) and test (bottom) vehicle.

Table 4
Wilcoxon signed-ranked test-showing p values obtained by comparing all 8 controls against each other (own + test vehicle).

Control type	Control number	1	2		3		4		5		6		7		8	
			Own	Test	Own	Test	Own	Test	Own	Test	Own	Test	Own	Test	Own	Test
Seat fore/aft	1		0.005	***NS***	0.024	***NS***	0.000	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.046	***NS***
Seat height	2				***NS***	***NS***	0.013	0.000	***NS***	0.000	0.077	0.000	0.000	0.000	***NS***	***NS***
Seat recline	3						0.000	0.000	0.012	0.000	0.021	0.000	0.000	0.000	***NS***	0.027
Head rest height	4								***NS***	0.086	***NS***	0.000	0.000	0.000	***NS***	***NS***
Lumbar support	5										***NS***	0.001	0.001	0.000	***NS***	***NS***
Steering wheel	6												0.000	0.000	0.068	***NS***
Seat belt	7														***NS***	***NS***
Other	8															

Table 5
Postural measurements captured from both vehicles comparing gender (n = 47).

Gender	Trunk-thigh angle		Arm flexion		Elbow angle		Knee angle		Ankle angle		Neck inclination	
	Own vehicle	Test vehicle	Own vehicle	Test vehicle	Own vehicle	Test vehicle	Own vehicle	Test vehicle	Own vehicle	Test vehicle	Own vehicle	Test vehicle
Male	99	102	36	36	131	131	117	116	91	92	46	47
Female	103	106	27	27	114	113	118	113	93	94	46	48
ANOVA test	***NS***	$p < 0.05$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	***NS***	***NS***	***NS***	***NS***	***NS***	***NS***

Table 6
Usability evaluation of seat controls in both vehicles (n = 47). Percentages calculated based on number of vehicles where feature was present.

Vehicles	What do you think of the reach distance of the following controls of the seat? (Reach)						How accessible are the following controls of the seat in terms of hand/arm access? (Hand/arm access)				How easy is it to operate the following controls of the seat? (Operability)			
	Too far (%)		OK (%)		Too close (%)		Easy (%)		Difficult (%)		Easy (%)		Difficult (%)	
	Test	Own	Test	Own	Test	Own	Test	Own	Test	Own	Test	Own	Test	Own
Seat lifter	13	4	79	89	6	0	64	66	36	34	94	75	6	26
Seat recliner	2	0	98	100	0	0	98	83	2	11	98	75	2	25
Lumbar support adjustment	15	16	51	63	34	21	26	63	75	37	75	58	23	42
Seat fore/aft adjustment	0	0	94	89	6	11	96	92	4	9	96	94	4	6
Head rest height adjustment	6	2	55	57	38	41	34	50	66	50	13	34	87	66

3.5. Functional performance

Functional performance tests were conducted as shown in Table 2.

3.6. Self-rated confidence

The oldest group (80 and over) had the lowest confidence compared to the other two groups ($p < 0.01$). Females reported less confidence compared to males ($p < 0.01$). No significant interaction was found between age and gender (ANOVA).

3.7. Visual contrast sensitivity

A significant decline in contrast sensitivity was observed with increasing age ($p < 0.01$). For example, only 60% of those 80 and over scored level 13 and above compared with 92% of 50–64 year olds. There was an interaction between the variables age and gender; ANOVA showed that the decline in contrast sensitivity was more common in older females ($p < 0.01$) for both eyes.

3.8. 9-hole peg-test

With increasing age, a decline in hand coordination/speed was observed for both hands ($p < 0.01$). No significant difference was found with gender. The average time taken to complete the test using the dominant hand for each age group follows as: 50–64 (20.7 s), 65–79 (22.9 s) and over 80s (27.3 s). For the non-dominant hand, results for each group were: 50–64 (21.6 s), 65–79 (25.2 s) and over 80s (30.1 s).

3.9. Clock reading test

Overall 9 participants failed the clock reading test comprising 20% of 65–79 year olds and 33% of participants over 80. Significant differences were found between age groupings but not gender; the older and oldest age groupings were more likely to fail the test ($p < 0.05$).

3.10. Arm reach test

The results showed that only one participant failed the arm reach test. This was a participant within the oldest group and they had an arm injury which prevented them completing the test.

4. Discussion

This study aimed to audit older drivers in order to understand challenges that they face in terms of their driving environment. It should be noted that issues identified could also be relevant to drivers of any age. For example, improved design of seat controls to make them more accessible to older drivers may also benefit younger drivers. The survey used the drivers' own cars in order to understand how drivers interact with their own, familiar, vehicle; the new car was used in order to highlight issues in an unfamiliar, but new, car. It was not designed to evaluate features of the new car per se; the researchers were free to design the study without constraint.

Many issues were identified related to the seat controls such as operating, accessing, reaching and finding; these were common for both vehicles. A high proportion of the sample reported difficulty with reach to the head rest height and the lumbar support adjustment. Schifferstein and Hekkert (2008) and Kroemer et al. (2001) recommend that products should be designed for use with one hand in front of the body and avoid the need to use both hands. In addition the authors state that reaching out to the sides or back whilst sitting is difficult (particularly for older individuals). In the current study the majority of participants were dissatisfied with the position of these controls and it would be beneficial to place them in a location where users are not required to reach to the side/back and to design the headrest to be operated by one hand only.

Ranganathan et al. (2001) identified that compared to a younger group, older people had 30% weaker handgrip force and 26% lower maximum pinch force. In the case of the head rest height adjustment, the control/lock is often small and requires a large force to push and release. Moving the head rest up/down was also challenging for the participants because for most vehicles the headrest release button needed to be pressed at the same time as adjusting the height making it a two-handed operation. In some cases hands were also used to steady the participant (e.g. Fig. 4) whilst the headrest was adjusted. This makes the headrest very difficult to adjust by older people.

The lumbar support adjuster accessibility was reported to be difficult in most vehicles (test vehicle: 74.5%) due to lack of sufficient space for the hand. The operation of lumbar support adjustments in participants' own vehicles was also commonly reported to be difficult. In the test vehicle this control was observed to be easier to rotate (smooth action), had a good grip and was able to be grasped with the tip of the fingers. However, it was located in a tight space for hand access and was also very difficult to locate. These controls were also reported to be difficult to operate (particularly in participants' own vehicles), as they were stiff and required extra force compared to the controls in the test vehicle in terms of the operation. This contrasts with general guidelines for controls that recommend the force or torque applied by an operator to actuate a control should be kept as low as possible (McCauley-Bush, 2012; Guastello, 2006) especially if the operation must be repeated often. It is recommended that controls such as lumbar support and seat recliner adjustments are designed to be operated with minimal effort. They should have a continuous actuation and they should be adjusted until the driver is satisfied with the seat position allowing continuous feedback to the operator.

The arm rest caused restriction in access to seat controls in some vehicles. Some participants had to open the door in order to allow sufficient space to make adjustments. Some did not understand what the controls were for. One example in this study was with an older female (89 years) who used a seat pad to increase seat height and was not aware that there was a lever on the side of her seat to do this; she had owned the car for 10 years without realising that the control existed. This highlights the need for adequate training/labelling in order for all owners to benefit from features that might be available in the vehicle.

The results from the video analysis provided a good understanding of the order of the tasks carried out during the seat set-up process. Knowing the sequence of the tasks carried out by users may improve the location and mapping of the controls when designing new vehicles. This will then make the set-up process easier for the user by knowing their expectations/preferences. Kroemer et al. (2001) recommends that controls should be grouped based on their sequential relations and in relation to their particular function (to reduce difficulty of reach and operation). Taking this into account, controls should be arranged depending on their operational importance and sequence, potentially through the use of link analysis (e.g. Zhao et al., 2010). This principle could be applied to the findings from the current study and based on the sequences identified, controls can be clustered. Many drivers in the cohort studied shared their car(s) with their partner and therefore seats were often adjusted whenever the driver changed. Hence, even if they were familiar with the car, they might often operate the controls. Currently, many controls are mechanical and comprise a mechanical linkage to the moving elements in the seat/cabin, and this provides practical constraints on engineering solutions. Recommendations on the type, action or location of seat controls are beyond the scope of this study.

The use of additional items (e.g. cushions to increase seat height) was commonplace, particularly for the over 80s. It is of interest that the use of additional items was also reported by Herriotts (2005) in a questionnaire survey. They found that up to 31% of older drivers reported using additional items in their own vehicle, 6% using a bead mat and 25% using a seat cushion (compared to only 2% of younger drivers). In the current study it was identified that three older females (60% of over 80s) used seat pads in their vehicles to increase their seat height. All of these females were short in stature and reported that the seat height was too low for them as even at maximum height they did not have a clear view of the road. This highlights that seat adjustment ranges may be inadequate for older females. This study found several design adaptations made by older drivers themselves. These included adding a foot rest, use of sponge to extend the seat cushion, using a shopping bag to reduce seat surface friction for ingress/egress, and placing a sponge in the door pocket to rest the knee. This shows that there is a clear need to focus on the design of seats and cabins to include the needs of people who are prepared to adapt their own vehicle to provide their own solutions. An alternative view might be that there is a potential after-market for modifications for specific user needs, paralleling the approach for seats designed for babies and children. It may be appropriate for manufacturers to provide more support to drivers (of all ages) in order to ensure that they understand the seat set up and how to adjust it; this could be part of an improved customer service offering.

For the current study there were no significant differences in the postures adopted by the different age groups apart from neck inclination; this was greater for both vehicles with increasing age. For example, the average neck inclination for each age group in the test vehicle was 50–64 (42°), 65–79 (48°) and over 80 (51°); and for their own vehicle 50–64 (41°), 65–79 (48°) and over 80 (48°). Kuo et al. (2009) obtained postural measurements (including neck slope and head tilt angle) from 22 older (60–83) and 24 younger (17–27 years) adults in seated and standing positions and also found that older participants had greater neck inclination angles. These findings may show that an increase in neck inclination in driving may be related to the spinal changes with age. For upper limb posture, females had lower arm flexion and elbow angles compared to males; similar results were reported by Porter and Gyi (1998). This indicates that females adopt their driving postures closer to the pedals/steering wheel compared to males, as confirmed from measurements of the seat position. A large proportion (more than 94%) of the whole sample fit within the comfort ranges suggested by Porter and Gyi (1998), indicating that the seat adjustment controls allowed the selection of a good posture for driving, despite many drivers finding it difficult to locate and operate controls. The study, by design, did not include a sample of drivers younger than 50 and therefore comparisons for those up to 50 is not possible. However, it is important to understand the preferred postures of drivers in order to optimise the position and adjustment of controls, and the position and design of safety systems such as airbags.

The suite of functional assessments provided an indication of the effects of ageing on the body particularly related to the driving task with the exception of the arm reach test. The self-rated confidence questionnaire showed that with increasing age there is a reduced confidence in the oldest group (over 80s, $p < 0.01$) and maybe one of the reasons older drivers stop driving. It may be that as drivers get older they become aware of their reduced capabilities and as a result this affects their confidence in carrying out specific driving tasks and they no longer feel safe. There were also significant differences by gender; females had lower confidence scores compared to males in general. There was no interaction between the variables age and gender, so this was not just associated with older females but it more related to older drivers in general (particularly over 80s) and females in the sample. Interestingly, the same questionnaire was used by Marottoli and Richardson (1998) but there were no significant differences by age and gender, but males were more likely to drive in conditions which may be considered more risky compared to females. It was also reported that the confidence scores were correlated with driving frequency ($p < 0.05$). These authors involved participants aged 72 years and older ($n = 165$) to complete the questionnaire (mean age 81.4

years) which may be a reason for not finding significant differences in age and gender.

The results of the clock reading test showed that 20% of 65–79 year olds and 33.3% of the over 80s failed the test due to their reduced upper shoulder flexibility (differences significant, $p < 0.01$). A study of older compared to younger drivers was conducted by Isler et al. (1997) looking at the head movements of drivers and its effects on the useful field of view. The study included various ages and it was identified that with increasing age the angle of maximum head movement decreases. Based on the assessment of hand coordination and dexterity using the 9-hole peg test, a decline in hand coordination and speed was observed for both hands with increasing age. This was also found by Wang et al. (2015), whereby the results obtained in both studies show a gradual decline with age for both males and females. The Hamilton Veale contrast sensitivity test showed that a decline in contrast sensitivity was observed with increasing age which was similar for both eyes tested together and separately. The studies conducted by Mäntyjarvi and Laitinen (2001) and Elliott et al. (1990), also reported that older participants had poorer contrast sensitivity than younger. With regard to the arm reach test (assessing shoulder flexibility), only one person failed and this was a participant within the oldest group with an arm injury which prevented them carrying out the test properly. When this is compared to the study conducted by Ball et al. (2006) with drivers aged 55 years and over, the proportion of the people failed the arm reach test was also small (less than 1% of a sample of 1910) participants.

This study only included current drivers and focused on design features of cars. Previous studies (E.g. Musselwhite and Shergold, 2013) used a longitudinal approach to understand the process of driving cessation for a small sample of individuals. They noted that the trigger was often a psychological switch in confidence in their own abilities, often triggered by external factors or a near-miss. However, it was noted that many drivers wanted to continue to drive well into their 80s, in order to maintain quality of life, an age when physical capabilities would be expected to be well in decline.

A limitation of this study is that since the audit was conducted in a static vehicle condition (no road driving), some participants reported they would prefer to do a test drive to ensure that the posture they selected was comfortable and to know if they needed to make further adjustments. In addition, the test vehicle was, by design, unfamiliar to the participants and they may have preferred to refine their posture after a period of time driving. However, a recent study conducted by Mansfield and Hazlett (2015) of 20 drivers (aged 18–24), compared the postures and seat positions selected using a laboratory buck and a real vehicle; they found that the differences between buck and real vehicle adjustments and postures were small. This may indicate that the driving posture selected would be similar for both vehicles although this would need further research with a sample of older drivers.

5. Conclusions

This research has enabled a detailed understanding of the user experience in relation to the vehicle cabin area and its impact on older drivers. It showed that many older drivers find it difficult to achieve an optimal driving position due to difficulties with some controls, and that it is common for adaptations to be made to the car. Cabin adjustments tended to start with basic seat adjustments, and finished with operation of the seat belt. The majority of the functional performance tests used in the study have shown reliability and have provided a way of understanding how declining physical capability can affect driving related tasks.

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References

Ball, K.K., Roenker, D.L., Wadley, V.G., Edwards, J.D., Roth, D.L., Mcgwin, G., Raleigh, R., Joyce, J.J., Cissell, G.M., Dube, T., 2006. Can high-risk older drivers be identified through performance-based measures in a department of motor vehicles setting? J. Am. Geriatrics Soc. 54 (1), 77–84.

Bhise, V.D., 2012. Ergonomics in the Automotive Design Process. CRS Press, Florida.

Bradley, M., Keith, S., Kolar, I., Wicks, C., Goodwin, R., 2008. What do older drivers want from new technologies? [online]. SPARC. Reading. [viewed 12/01/2012]. Available from: http://www.sparc.ac.uk/media/downloads/executivesummaries/execsummarybradley.pdf.

Creighton, H., 2014. Europe's Ageing Demography: ILC-UK 2014 Factpack [Homepage of ILC]. Available. http://www.ilcuk.org.uk/index.php/publications/publication_details/europes_ageing_demography [01/12, 2014].

Charlton, A.U., Lovell, R.K., Terrington, N.S., Thomas, S.A., 2002. Review of tests contributing to the occupational therapy off-road driver assessment. Aust. Occup. Ther. J. 52 (1), 57–74.

Dvla, 2010. Driving License Holding and Vehicle Availability. Driver and Vehicle Licensing Agency, Swansea [viewed 23/05/2016]. Available from. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/8933/nts2010-02.pdf.

Eby, D.W., Molnar, L.J., Nation, A.D., Shope, J.T., Kostyniuk, L.P., 2006. Development and Testing of an Assessment Battery for Older Drivers. UMTRI-2006-04. The University of Michigan Transportation Research Institute, Michigan: USA.

Elliott, D.B., Sanderson, K., Conkey, A., 1990. The reliability of the Pelli-Robson contrast sensitivity chart. Ophthalmic Physiol. Opt. 10 (1), 21–24.

Guastello, S.J., 2006. Human Factors Engineering and Ergonomics: a Systems Approach. Lawrence Erlbaum, London.

Gyi, D.E., 2013. Driving posture and healthy design. In: Gkikas, N. (Ed.), Automotive Ergonomics : Driver-vehicle Interaction. CRC, London, pp. 123–131.

Haymes, S.A., Chen, J., 2004. Reliability and validity of the melbourne edge test and high/low contrast visual acuity chart. Optom. Vis. Sci. 81 (5), 308–316.

Herriotts, P., 2005. Identification of vehicle design requirements for older drivers. Appl. Ergon. 36 (3), 255–262.

Institute of Advanced Motorists, 2012. More than a Million Drivers Now Aged over 80. Institute of Advanced Motorists, London [viewed 22/05/2012]. Available from. http://www.iam.org.uk/news/latest-news/983-more-than-a-million-drivers-now-aged-over-80.

Isler, R.B., Parsonson, B.S., Hanssson, G.J., 1997. Age related effects of restricted head movements on the useful field of view of drivers. Accid. Anal. Prev. 29 (6), 793–801.

Karali, S., Gyi, D.E., Mansfield, N.J., 2016. Driving a better driving experience: a questionnaire survey of older compared with younger drivers. Ergonomics 59. http://dx.doi.org/10.1080/00140139.2016.1182648.

Key, C.E.J., Morris, A.P., Mansfield, N.J., 2016. Situation Awareness: its proficiency amongst older and younger drivers, and its usefulness for perceiving hazards. Transp. Res. Part F Traffic Psychol. Behav. 40, 156–168.

Kroemer, K.H.E., Kroemer, H.B., Kroemer-elbert, K., 2001. Ergonomics: How to Design for Ease and Efficiency, second ed. Prentice Hall, NJ.

Kuo, Y., Tully, E.A., Galea, M.P., 2009. Video analysis of saggital spinal posture in healthy young and older adults. J. Manip. Physiol. Ther. 32 (3), 210–215.

Kyung, G., Nussbaum, M.A., 2010. Assessment of aging effects on drivers' perceptual and behavioral responses using subjective ratings and pressure measures. In: Spink, A.J., Grieco, F., Krips, O.E., Loijens, L.W.S., Noldus, L.P.J.J., Zimmerman, P.H. (Eds.), Proceedings of Measuring Behavior 2010, 24-27 August 2010, pp. 318–321.

Mäntyjärvi, M., Laitinen, T., 2001. Normal values for the Pelli-Robson contrast sensitivity test1. J. Cataract Refract. Surg. 27 (2), 261–266.

Marottoli, R.A., Richardson, E.D., 1998. Confidence in, and self-rating of, driving ability among older drivers. Accid. Anal. Prev. 30 (3), 331–336.

Mansfield, N.J., Hazlett, B., 2015. Lab trials on trial: prefered postures in an automotive test rig (buck) and the real vehicle. In: Sharples, S., Shorrock, S., Waterson, P. (Eds.), Contemporary Ergonomics and Human Factors 2015, April 2015 2015. Taylor & Francis, pp. 482–487.

Mccauley-Bush, P., 2012. Ergonomics: Foundational Principles, Applications, and Technologies. CRC Press.

Middleton, H., Westwood, D., Robson, J., Kok, D., 2005. Assessment and decision criteria for driving competence in the elderly. In: Underwood, G. (Ed.), Traffic & Transport Psychology. Elsevier, UK, pp. 101–113.

Musselwhite, C., Haddad, H., 2008. Prolonging Safe Behaviour through Technology: Attitudes of Older Drivers. SPARC, Reading [Viewed 25/02/2012]. Available from. http://www.sparc.ac.uk/media/downloads/executivesummaries/exec_summary_musselwhite.pdf.

Musselwhite, C.B.A., 2016. Assessment of computer-based training packages that may improve the safety older people's driver behaviour. In: Proceedings of Universities' Transport Studies Group, Bristol, UK, January 2016.

Musselwhite, C.B.A., Shergold, I., 2013. Examining the process of driving cessation in later life. Eur. J. Ageing 10, 89–100.

Pheasant, S., Haslegrave, C.M., 2006. Bodyspace: Anthropometry, Ergonomics and the Design of Work, thi[rd] ed. CRS Press, Florida.
Porter, J.M., Gyi, D.E., 1998. Exploring the optimum posture for driver comfort. Int. J. Veh. Des. 19 (3), 255–266.
Ranganathan, V.K., Siemionow, V., Sahgal, V., Yue, G.H., 2001. Effects of aging on hand function. J. Am. Geriatrics Soc. 49 (11), 1478–1484.
Schifferstein, H., Hekkert, P., 2008. Product Experience, 1st ed. Elsevier, Boston.
Smith, Y.A., Hong, E., Presson, C., 2000. Normative and validation studies of the Nine-hole Peg Test with children. Percept. Mot. Skills 90 (3), 823–843.
Smith, D.B.D., Meshkati, N., Robertson, M.M., 1993. The older driver and passenger. In: Peacock, B., Karwowski, W. (Eds.), Automotive Ergonomics. Taylor & Francis, London, pp. 453–471.
Statista, 2016. Cars Bought in the UK by Gender and Age [viewed 26/05/2016]. Available from. http://www.statista.com/statistics/300027/cars-bought-in-united-kingdom-by-gender-and-age/.
Tamiya, N., Noguchi, H., Nishi, A., Reich, M.R., Ikegami, N., Hashimoto, H., Shibuya, K., Kawachi, I., Campbell, J.C., 2011. Population ageing and wellbeing: lessons from Japan's long-term care insurance policy. Lancet 378 (9797), 1183–1192.
Wang, Y., Bohannon, R.W., Kapellusch, J., Garg, A., Gershon, R.C., 2015. Dexterity as measured with the 9-Hole Peg Test (9-HPT) across the age span. J. Hand Ther. 28 (1), 53–60.
Williams, M.A., Attridge, A., Pitts, M., 2011. User-centred design and evaluation of automotive seat adjustment controls. Int. J. Veh. Des. 55 (2–4), 119–138.
Zhao, Y., Hignett, S., Mansfield, N.J., 2010. Computerised link analysis. In: Proceedings of 3rd International Conference on Applied Human Factors and Ergonomics, July 2010, Miami, USA.