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Enhancing digital driver models: Identification of distinct postural strategies used by drivers

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Driver workspace design and evaluation is, in part, based on assumed driving postures of users and determines several ergonomic aspects of a vehicle, such as reach, visibility and postural comfort. Accurately predicting and specifying standard driving postures, hence, are necessary to improve the ergonomic quality of the driver workspace. In this study, a statistical clustering approach was employed to reduce driving posture simulation/prediction errors, assuming that drivers use several distinct postural strategies when interacting with automobiles. 2-D driving postures, described by 16 joint angles, were obtained from 38 participants with diverse demographics (age, gender) and anthropometrics (stature, body mass) and in two vehicle classes (sedans and SUVs). Based on the proximity of joint angle sets, cluster analysis yielded three predominant postural strategies in each vehicle class (i.e. 'lower limb flexed', 'upper limb flexed' and 'extended'). Mean angular differences between clusters ranged from 3.8 to 52.4° for the majority of joints, supporting the practical relevance of the distinct clusters. The existence of such postural strategies should be considered when utilising digital human models (DHMs) to enhance and evaluate driver workspace design ergonomically and proactively.

Statement of Relevance: This study identified drivers' distinct postural strategies, based on actual drivers' behaviours. Such strategies can facilitate accurate positioning of DHMs and hence help design ergonomic driver workspaces.

Keywords: asymmetric driving posture; cluster analysis; comfortable driving posture; preferred driving posture; postural strategies

1. Introduction

Digital human models (DHMs) have been extensively used in automotive design, especially for driver workspace design, to achieve diverse benefits such as reduced design/engineering costs and time and ergonomic quality improvement (Porter *et al.* 1993, Hanson *et al.* 1999, Park *et al.* 2004, Chaffin 2005, 2007). A variety of methods (e.g. neural networks, regression, Kalman filtering, kinematics, inverse kinematics and optimisation) have been used to model and predict postures and movements of people (Hanson *et al.* 1999, Reed *et al.* 2002, Pinho *et al.* 2005, Chaffin 2007). DHM tools coupled with these methods, however, are acknowledged as requiring additional sophistication and/or accuracy when used to simulate human postures and movements (Chaffin *et al.* 1999, Chaffin 2005, 2007), presumably including those of drivers. To increase the validity of ergonomic design and analysis using a DHM, characteristics of human behaviours identified for postures and movements should be embedded in a DHM tool (Chaffin 2005).

A 'driving posture' is the posture adopted inside a driving workspace when interacting with a vehicle. It is the resulting posture after the upper and lower extremities reach their respective designated targets. In a vehicle equipped with an automatic transmission, for example, a driver's upper limbs and left lower limb have loosely defined target locations (e.g. anywhere on the steering wheel for at least one hand and on/around the foot rest, if available, for the left foot), while the right lower limb has relatively fixed target locations (i.e. mostly on the accelerator (gas) pedal or on the brake pedal). After reaching these targets, the arms and the right leg are repetitively engaged in controlling movements for steering and pedalling tasks, with other intermittent reach and control movements for the arms (e.g. for transmission gear shift, ventilation adjustment and radio tuning). Motion prediction algorithms, such as inverse kinematics, can be used to specify a normal driving posture (e.g. Reed *et al.* 2002), which is not only a terminal (though not static) posture of these initial reaching motions (to the wheel and pedals), but also an initial or intermediate posture for other reaching and controlling motions throughout the course of driving. It should be noted here that the geometrical relationship between the driver and targets

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can be altered at any time during and outside of these reaching movements according to any required adjustments of the seat and/or the steering wheel.

Although seated in a fairly confined space, drivers adopt diverse driving postures. Even two drivers of a similar body size may adopt different postures (Kolich 2008). In addition to reaching and controlling movements, drivers tend to change their driving posture intermittently in order to reduce discomfort induced by postural fixity (Akerbloom 1948, Jenny *et al*. 2001, Andreoni *et al*. 2002, Dhingra *et al*. 2003). Individual attributes (e.g. age, gender and anthropometry) and vehicle factors (e.g. vehicle class, interior geometry and driving venue) have also been demonstrated to affect drivers' reaching or sitting postures (Chaffin *et al*. 2000, Park *et al*. 2000, Reed *et al*. 2000, Hanson *et al*. 2006, Kyung 2008). Given that substantial variability exists among driving postures, posture specification and prediction inevitably comes with some degree of error. If these heterogeneous driving postures can be classified by their inherent similarity, however, errors involved in simulating driving posture can be reduced. Applying a prediction method to partitioned data would improve accuracy of modelling and simulation of postures and movements, as each subgroup would be more homogeneous than the entire dataset and several distinct reaching or posturing techniques might be involved when adopting driving postures.

Cluster analysis, an exploratory technique, divides a set of objects (in this case, driving postures) into two or more groups (called clusters), based on the proximity of the objects. The result is that each cluster is internally homogeneous and highly heterogeneous with other clusters (Hair and Black 2000). In contrast to discriminant analysis, it does not require that the number of clusters be specified a priori. Therefore, it seems a more appropriate technique for the current problem of interest (i.e. to determine drivers' postural strategies). Accordingly, cluster analysis can be used to identify homogeneous groups of driving postures, which can be considered as postural strategies or initial reaching techniques. Indeed, cluster analysis has previously been applied to the classification of human movements and postures. Examples include alternative lifting techniques (Park and Singh 2004) and gait patterns of patients following stroke (Mulroy *et al*. 2003).

Although a few published studies have addressed classification of sitting or driving postures, none has applied cluster analysis to driving postures described by joint angles. Beach *et al*. (2005) identified static and dynamic strategies for seated postures lasting 2 h in an office chair. Static sitting strategy was defined as 'maintaining a sitting posture that was within a 15% range of lumbar flexion for at least 85% of the collection time' (p. 148). Using an interface pressure measurement system on a car seat pan, Andreoni *et al*. (2002) investigated driver sitting strategies and qualitatively identified two strategies (i.e. 'the ischiatic and trochanteric strategies', p. 518) according to the anatomical region at which the peak pressure was observed. Earlier, Andreoni *et al*. (1999), using pressure distribution on a car seat back, identified three driver sitting strategies for the upper body ('dorsal sitting' with uniform pressure at the upper back, 'upper scapular sitting' with higher pressure at the scapula and 'lumbar sitting' with high pressure at the lumbar area; p. 2). The two studies by Andreoni *et al*. (1999, 2002) suggest that there may exist six sitting strategies in the context of driving.

None of these earlier strategies, however, can be used to specify driving postures of DHMs because their postural specification does not effectively describe the position/orientation of the entire body. There is also a fundamental limitation in describing whole-body posture quantitatively using interface pressure, because a pressure-based description is inevitably limited to those body parts in contact with the seat (i.e. at best from the upper back to the knees). Additionally, current computer-aided design tools have not advanced to the point where driving postures can be effectively modelled based on interface pressure between the driver and seat. Hence, it is necessary to investigate drivers' postural strategies by quantifying joint angles, rather than interface pressure, in order to specify an entire driving posture (i.e. from the wrists to the neck and down to the ankles) in an easier and effective way within currently available DHM tools.

Confined driver workspaces, determined by considering the design space typically available for a selected vehicle style and drivers' comfort and safety, may hinder drivers when adopting preferred driving postures. A previous study (Kyung *et al*. 2007) quantified drivers' responses to slight changes in their preferred driving postures. In that study, participants' hip joint centres (HJC) were randomly moved to one of 20 predefined locations around the original driver-selected HJC location; this was achieved in an adjustable driving rig that provided more extensive adjustment ranges than available currently in standard automobiles. Groups with different age, gender and stature dimensions showed distinct responses to these altered postures. This suggests that several postural strategies would likely be adopted when a driver workspace does not provide a sufficient adjustment range or space, prohibiting drivers from adopting their preferred driving posture (i.e. when a postural adaptation is needed).

Standards from the Society of Automotive Engineers, such as J1517 (1998) and J941 (2002), have been used widely to measure or determine accommodation levels of the driver workspace. However, these standards are acknowledged as insufficient to accommodate populations at the extremes (e.g. 5th percentile females and 95th percentile males; Kyung 2008). Hence, these groups may seek to compensate for any spatial deficiency of a driving workspace in a way that minimises their discomfort. In addition, while determining comfortable driving postures, Kyung (2008) conjectured that at least two sitting strategies are present, based on the existence of two discontinuous comfortable angular ranges at most joints. Therefore, further investigation is warranted to determine exactly how many strategies drivers indeed use and whether these strategies show a clear association with driver attributes, such as age, gender and stature.

The goal of this study, therefore, was to identify drivers' postural strategies for two vehicle classes (compact sedan and compact SUV) and to examine whether these strategies can be clearly divided by driver attributes (i.e. age, gender and stature). A longer-term goal is to use any identified strategies to increase the accuracy of driving posture simulation and to facilitate improved ergonomic design and evaluation of a driver workspace that involves DHM tools.

2. Experimental methods

2.1. *Overview of experiment*

This is a secondary analysis of the joint angle data collected and used in a previous study (Kyung 2008). As such, experimental methods, except for data analysis, were identical. Only a brief summary of the experiment is given here; for more information on definitions of joint angles, data collection procedures and experimental conditions, the reader is referred to the prior report. A total of 38 participants completed six experimental sessions, each involving $\sim$20 min of driving. In total, 16 joint angles were obtained, via anatomical landmarks whose spatial configuration was determined using a coordinate measurement machine. These driving sessions combined two vehicle classes (sedan and SUV), two driving venues (laboratory-based and field-based), and two seats (from vehicles ranked high and low by J.D. Power and Associates' (2005) comfort score) per vehicle class. At the time of study, only from these two vehicle classes could two samples per vehicle class be contrasted by J.D. Power comfort score (one rated high and the other rated low at vehicle level). More specifically, sedans were selected from the compact sedan segment and SUVs from the compact SUV segment, both in the USA. The venue effect (laboratory-based setting with a low fidelity driving simulator vs. field-based setting with actual on-the-road driving) was investigated, since differences between laboratory and field settings in the importance of visual information for driving, and in vibration exposure, might lead to different driving postures. In the laboratory setting, both seats from the high- and low-ranked vehicles were used for each vehicle class to investigate seat effects on subjective ratings and postural changes. Except for the seat design attributes, occupant packaging was shared in each vehicle class (e.g. designed seating reference point, seat cushion and back angles were set equal to those of the high-ranked vehicle). Participants completed three sessions (two in the laboratory and one in the field) for each vehicle class. Participants were experienced ($\geq$2 years), licensed drivers, with normal or corrected-to-normal eye vision (tested in the laboratory, prior to the first session) and no current musculoskeletal disorders (self-reported) and were selected from two age groups (27 aged 20–35 years; 11 aged 60 years or over), both genders (18 males; 20 females) and three stature groups (14 participants $<$165 cm; 12 participants 165–175 cm; 12 participants $>$175cm). A targeted recruitment was used to achieve age groups that were reasonably matched for stature and BMI: in the younger and older groups, respective means (SD) for stature and BMI were 168.2 (11.7) vs. 170.0 (11.6) cm and 25.5 (5.2) vs. 24.1 (3.9) kg/m^2. Each participant completed an informed consent procedure, approved by the local Institutional Review Board, prior to the first experimental session.

2.2. *Data analysis*

As effects of vehicle class on driving postures were evident at several joints (i.e. eight of 16 joints; Kyung 2008), joint angle data separated by vehicle class were used in cluster analysis to group drivers by the similarity of their postures as described by joint angles. The datasets were first standardised (using the mean and standard deviation of each joint angle) and then Ward's method, one of the hierarchical clustering procedures, was used to identify several subgroups that would represent different postural strategies. The final number of clusters was determined by visually examining each clustered dendrogram. After repeated-measures multivariate ANOVA (MANOVA) was conducted (Weinfurt 1994), univariate repeated-measures ANOVA was used to investigate whether joint angles were different between clusters, with the Tukey's HSD test for post-hoc pair-wise comparisons. Additionally, to investigate whether drivers adopted the same postural strategies across two vehicle classes and/or across two driving venues, the total number of strategies employed by each driver was counted.

Effects were considered significant when $p \leq 0.05$. One female participant finished only the laboratory sessions; hence, the number of joint angle datasets for each vehicle class was reduced from 114 (38 participants × 3 sessions per participant per vehicle class) to 113.

3. Results

3.1. Driving posture in compact sedans

Three subgroups emerged based on the similarity (or dissimilarity) of the 113 sets of 16 joint angles that described driving postures measured in the sedan sessions (Figure 1). The three clusters identified (Figure 2) were also different from each other in terms of their size and composition (Table 1). The first cluster was composed of 60 datasets and was characterised as having the smallest mean joint angles for the elbows and shoulders among the three clusters. This cluster was termed 'upper limb flexed' (UL-flexed). The second cluster, containing 43 datasets, had the smallest mean joint angles for the hips, knees and ankles. This cluster was termed 'lower limb flexed' (LL-flexed). The third cluster consisted of the remaining 10 datasets and came exclusively from younger individuals. This cluster had the most extended driving postures, except for wrist angles, and was termed 'extended'. MANOVA showed that there were significant ($p < 0.0001$) cluster effects on the 16 joint angles as a group. Subsequent ANOVA identified significant ($p \leq 0.04$) cluster effects on each of 14 joint angles except for the neck and torso (Figure 2), with mean differences ranging from 4.9 to 52.4° for the right knee and elbow, respectively.

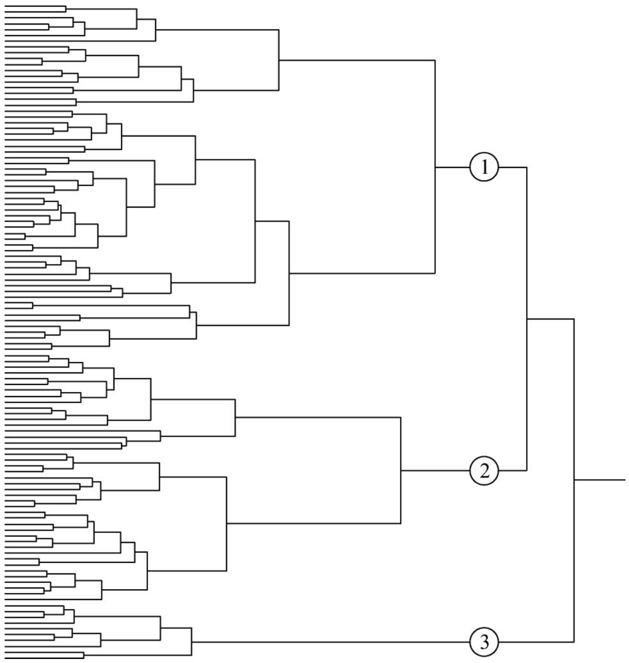

Figure 1. Clustered dendrogram for driving postures in sedans (cluster numbers are in circles; branch length indicates dissimilarity between data).

3.2. Driving postures in compact SUVs

Consistent with the sedan sessions, three distinct subgroups were also identified by cluster analysis in the SUV sessions (Figures 3 and 4; Table 2). These three groups were termed the same as before, but there were slight differences in size and composition between corresponding clusters from two vehicle classes. The first cluster, very similar to the sedan sessions, consisted of 42 datasets and represented driving postures with the smallest mean joint angles for the elbows and shoulders (UL-flexed). The second cluster, containing 39 datasets, was characterised as having the right lower limb closest to the pedals since it had the smallest mean joint angles for the knees and left ankle (LL-flexed). This group also had the smallest mean joint angle for the right knee as before, but not for the right ankle. The third cluster comprised 32 datasets and most of the data (30 of 32) were from the younger group, similar to the sedan sessions. This third cluster also had the largest joint angles for the upper and lower body except for the wrists and left ankle (extended). MANOVA indicated significant ($p < 0.0001$) cluster effects on the set of 16 joint angles. Subsequent ANOVA revealed that there was a significant ($p \leq 0.04$) cluster effect on each of the 16 joint angles, with the mean differences ranging from 3.8 (for the right ankle with the foot plane) to 37.8° (for the left elbow).

3.3. Consistency of postural strategies

As seen in sections 3.1 and 3.2, three postural strategies were consistently identified in both sedan and SUV classes (Tables 1–2; Figure 5), as well as both driving venues (Tables 1–2). At the individual level, however, inconsistency in the use of postural strategies was observed, in that most drivers did not maintain a single postural strategy. Specifically, only 13 participants (34%) used one strategy across the two vehicle classes and/or the two driving venues, while 16 participants (42%) used two strategies and nine participants (24%) used all three strategies.

4. Discussion

DHMs have been widely used during driver workspace design to proactively evaluate and ensure vehicle interior ergonomics without physical prototypes and to

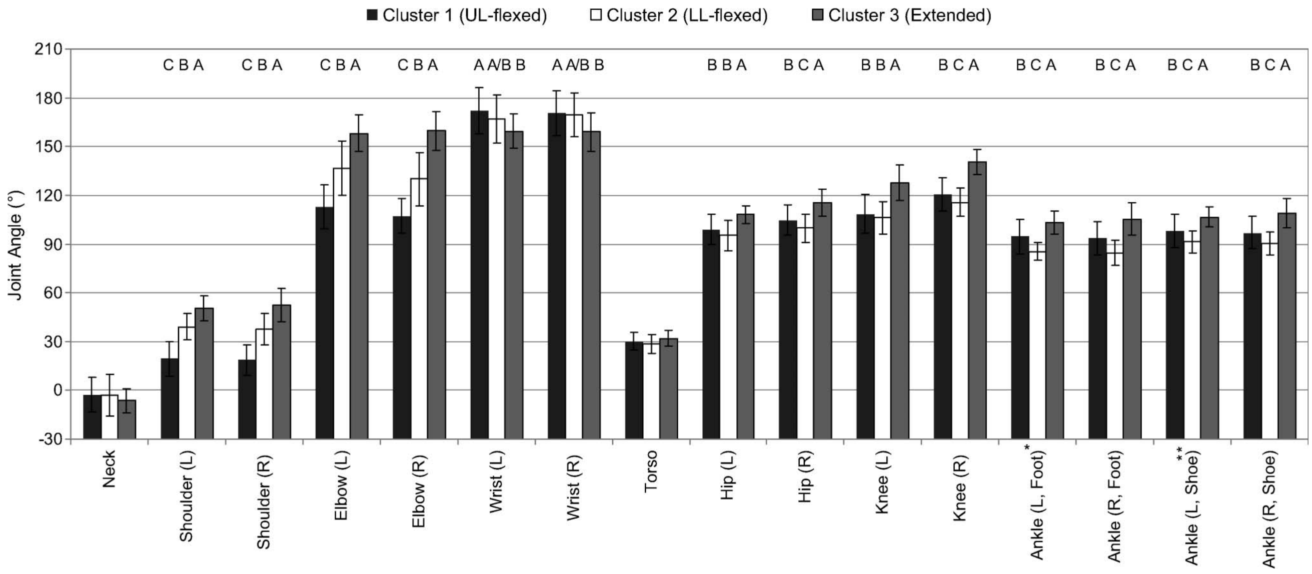

Figure 2. Mean joint angles in the three postural strategies – sedans. Differences between clusters are significant for all joints except the neck and torso. Error bars indicate SD. Post-hoc grouping (A/B/C) are shown at the top. *Indicates ankle angle defined between the bare foot bottom and lower leg; **Indicates ankle angle defined between the shoe bottom and lower leg. UL-flexed = upper limb flexed; LL-flexed = lower limb flexed.

retrospectively investigate and compare competitors' production vehicles with a vehicle under development. More sophisticated DHMs, however, are still needed with regard to their accuracy in specifying and predicting driving postures. The standard driving postures selected for DHMs influence the ergonomic quality of driver workspace in terms of drivers' postural comfort or alertness level (Diffrient *et al.* 1990), reach and visibility (Chaffin 2007). Hence, major, if not all, representative behavioural characteristics of drivers should be built into a DHM in order for it to be capable of moving and posing similar to actual drivers. Based on the findings in the current and previous studies (Andreoni *et al.* 1999, 2002, Kyung 2008, Kyung and Nussbaum 2008), the following three behaviours, at a minimum, should be considered when modelling a digital driver: 1) postural strategy; 2) postural asymmetry; 3) lateral imbalance of the whole-body posture. The need for more sophisticated DHMs and the relevance of these three behaviours to the development of more accurate digital driver models are further discussed below.

DHM tools need to be improved further to ensure their validity for use in design and evaluation tasks (Chaffin 2007). Several commercial software packages such as RAMSIS^{TM} (Human Solutions, Troy, MI, USA), Safework^{TM} (Safework, Inc., Montréal, Quebec, Canada), JACK^{TM} (Siemens PLM Software, Plano, TX, USA) and CATIA V5^{TM} (IBM and Dassault, Armonk, NY, USA) have been used for human modelling and simulation in a virtual design space. Postural discomfort of a DHM is linked to a discomfort database built into the software package (e.g. Wisner and Rebiffé 1963 and Diffrient *et al.* 1990 for the Human Builder module in CATIA V5). Since previous studies on comfortable driving postures or other human postures have not extensively or explicitly considered individual attributes such as gender, age and stature (as addressed by Chaffin *et al.* 2000, Park *et al.* 2000, Dunk and Callaghan 2005, Kyung 2008), asymmetry of driving postures (as addressed in Hanson *et al.* 2006, Kyung 2008), vehicle factors (as addressed in Kyung 2008) or the need for separate measures of comfort and discomfort (as addressed in de Looze *et al.* 2003, Kyung 2008), these limitations remain in the DHM software as well as any ergonomic analysis stemming from it.

In the present study, drivers' postural strategies were identified by dividing an initially diverse set of driving postures into several homogeneous groups using cluster analysis. Three consistent clusters (strategies) were identified in two vehicle classes and two driving venues. The specific strategies were 'UL-flexed', 'LL-flexed' and 'extended', with each representing a distinct postural strategy adopted by drivers. In particular, the third cluster (extended) corresponded to the driving postures of younger individuals regardless of vehicle class. As such, when designing a driver workspace the upper boundary posture, which is used to simulate drivers seated

Table 1. Composition of the three clusters representing drivers' postural strategies – sedan.

Cluster (Name)	Cluster 1 (UL-flexed)		Cluster 2 (LL-flexed)		Cluster 3 (Extended)	
Total no. of datasets*	60 (51/9)		43 (17/26)		10 (8/2)	
Younger vs. older	38	22	32	11	10	0
Short (M/F)†	16 (0/16)	13 (2/11)	5 (0/5)	2 (1/1)	6 (3/3)	0
Middle (M/F)†	14 (6/8)	3 (2/1)	10 (4/6)	6 (4/2)	2 (2/0)	0
Tall (M/F)†	8 (6/2)	6 (6/0)	17 (13/4)	3 (3/0)	2 (2/0)	0
Mean (SD) stature (cm)	167.6 (11.6)		174.1 (10.6)		167.1 (11.0)	

UL-flexed = upper limb flexed; LL-flexed = lower limb flexed.

*Number of datasets collected from laboratory and field sessions.

†Number of males/females.

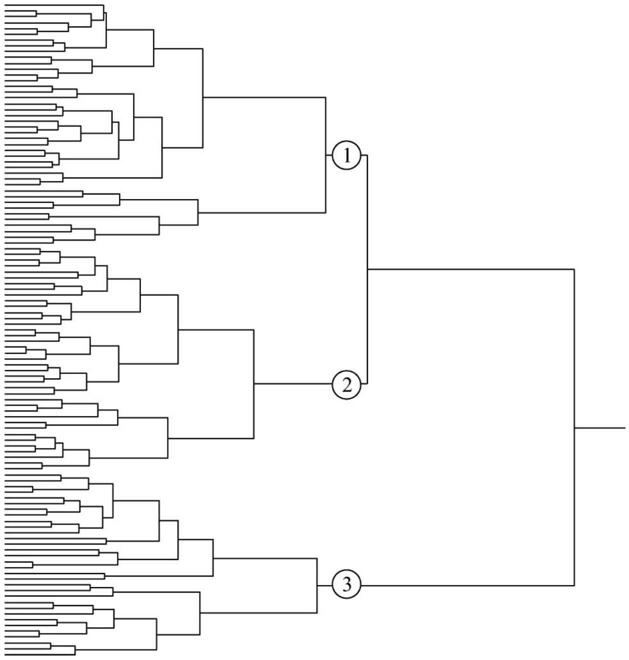

Figure 3. Clustered dendrogram for driving postures in SUVs.

farthest away from the steering wheel, should represent those of taller, younger drivers adopting this strategy. In contrast, the compositions (age, gender and stature) of the other two clusters exhibited inconsistency across the two vehicle classes, indicating that the interior geometry and/or parts might influence which postural strategy drivers employ. Indeed, inconsistency in postural strategies was observed within an individual driver; only one-third of drivers adopted one strategy, whereas the rest used two or three strategies. Hence, not all of the three clusters identified for each vehicle class were clearly divided by demographic variables. Rather, the first two clusters were composed of mixed populations, although between the first two strategies, UL-flexed was more frequently adopted by short individuals (47 and 48% of the total dataset for sedan and SUV, respectively) and LL-flexed by tall individuals (46 and 50%).

The main application of the postural strategies identified in this study is in improving driver workspace design. If each strategy is considered in the driver workspace design process, several important ergonomic attributes can be addressed. For example, each strategy can be used to more accurately estimate a driver's seating location and eye location (usually those of a DHM) within the driver workspace. This also results in changes in other major ergonomic quality checkpoints with regard to visibility, hand reach and roominess. Hence, applying the strategies identified in this study can aid in designing a more effective driver workspace in terms of seating position, visibility and reach.

More general interpretation and application of the current findings are also possible. For example, Faraway's (1997) quadratic regression model predicts joint angles over time and includes a term to explain demographic variability in human posture. The current result (i.e. the existence of different strategies) supports that his model might predict driving posture more accurately by including additional terms to account for variability due to postural strategies and effects of vehicle factors (e.g. interior geometry). As identified in this study, standard postures used to interact with a vehicle (i.e. to steer the wheel, control the pedals and initiate other reaching movements) can be categorised into three strategies. Therefore, the trajectory estimator for driving postures (terminal postures of initial reaching movements) should have three versions, each accounting for a different postural strategy, in order to yield more accurate estimations and predict movements more similar to actual driver behaviours. More generally, simulated motions should have improved accuracy if these strategies are incorporated into current motion generating algorithms/frameworks, such as the memory-based motion simulation of Park *et al.* (2004) or the motion framework of Reed *et al.* (2006) (Figure 6). The current

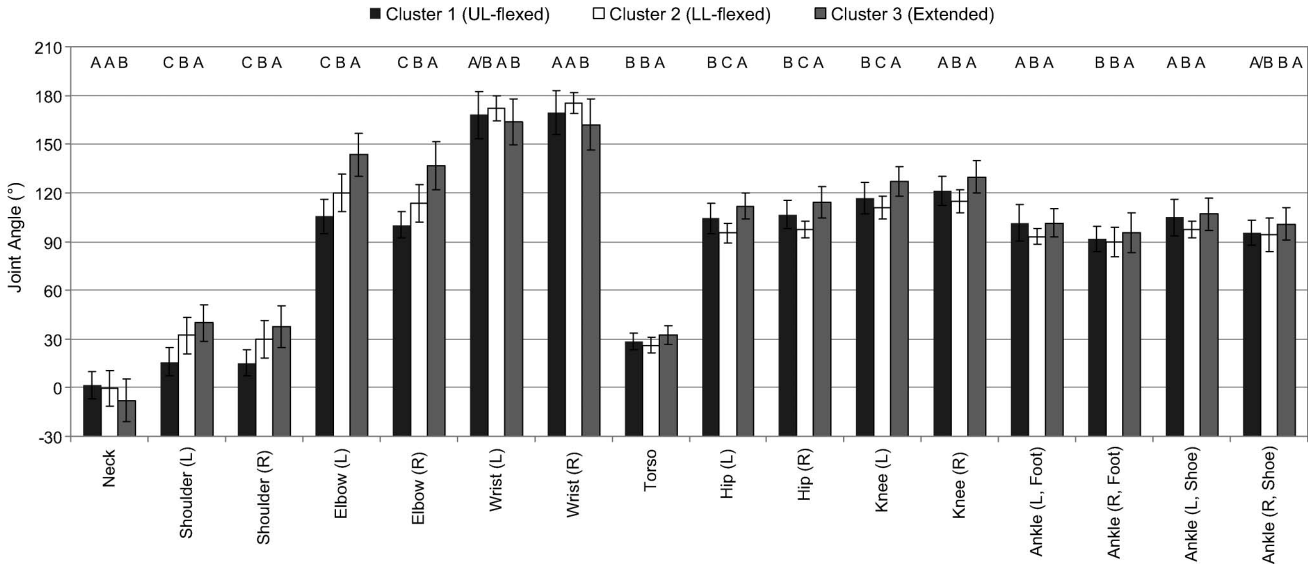

Figure 4. Mean joint angles of three postural strategies – SUVs (All joints are significant; Error bars indicate SD. Tukey's HSD grouping (A/B/C) is shown at the top). UL-flexed = upper limb flexed; LL-flexed = lower limb flexed.

Table 2. Composition of the three clusters representing drivers' postural strategies – SUV.

Cluster (Name)	Cluster 1 (UL-flexed)		Cluster 2 (LL-flexed)		Cluster 3 (Extended)	
Total no. of datasets*	42 (28/14)		39 (27/12)		32 (21/11)	
Younger vs. older	25	17	25	14	30	2
Short (M/F)[†]	11 (0/11)	10 (0/10)	3 (0/3)	4 (2/2)	13 (3/10)	1 (1/0)
Middle (M/F)[†]	11 (4/7)	1 (1/0)	7 (5/2)	7 (4/3)	8 (3/5)	1 (1/0)
Tall (M/F)[†]	3 (1/2)	6 (6/0)	15 (11/4)	3 (3/0)	9 (9/0)	0
Mean (SD) stature (cm)	166.2 (11.4)		175.2 (10.7)		168.8 (10.6)	

UL-flexed = upper limb flexed; LL-flexed = lower limb flexed.
*Number of datasets collected from laboratory and field sessions.
[†] Number of males/females.

study identified three strategies in the driving context, while Burgess-Limerick (2003) suggested three strategies for manual lifting (i.e. squat, stoop and freestyle). Using human posture and motion data partitioned by inherent strategies is expected to reduce errors when predicting human postures and motions, as each partitioned set of data has less variability than the entire data. In other words, this strategy-based approach decomposes the variability inherent in human postures and motions and can, thereby, provide more homogeneous datasets to the relevant prediction method.

Further improvements in accuracy and workspace design can be achieved by accounting for bilateral asymmetry of driving postures in a DHM. Although driving postures have been usually assumed to be bilaterally symmetric in many existing studies (Rebiffé 1969, DIN 1981, Dupuis 1983, HdE 1989, Bubb 1992, Porter and Gyi 1998, Park *et al.* 2000, Reed *et al.* 2002, Vogt *et al.* 2005), more recent studies (Hanson *et al.* 2006, Kyung 2008) have suggested otherwise. Considering the close relationships between bilateral sides in balance and movement of the whole body, even in a seated posture within a confined driver workspace, the asymmetry of driving postures should be taken into account when specifying driving postures and designing the driver workspace. Drivers may get better (or more balanced) postural support from a design in which drivers' actual behaviours (e.g. using asymmetric posture) are closely reflected.

In addition to the bilateral asymmetry of driving posture, there appears to be a bilateral imbalance in interface pressures. Recent work (Kyung and Nussbaum 2008) shows higher absolute and relative pressures at a drivers' left buttock, indicating a tendency to lean toward the left side (in addition to backward leaning). Andreoni *et al.* (2002) also found a higher peak pressure in a drivers' left buttock. The

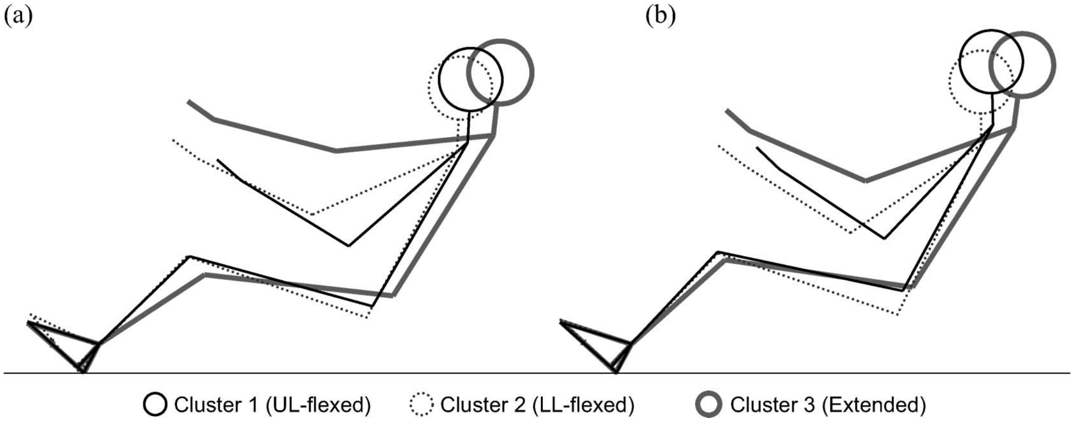

Figure 5. Schematic comparison of the three postural strategies for a single driver: (a) sedan; (b) SUV. Only the right limbs are shown for clarity. Balls of the feet (two-thirds from heel) are aligned vertically and heels are aligned horizontally. UL-flexed = upper limb flexed; LL-flexed = lower limb flexed.

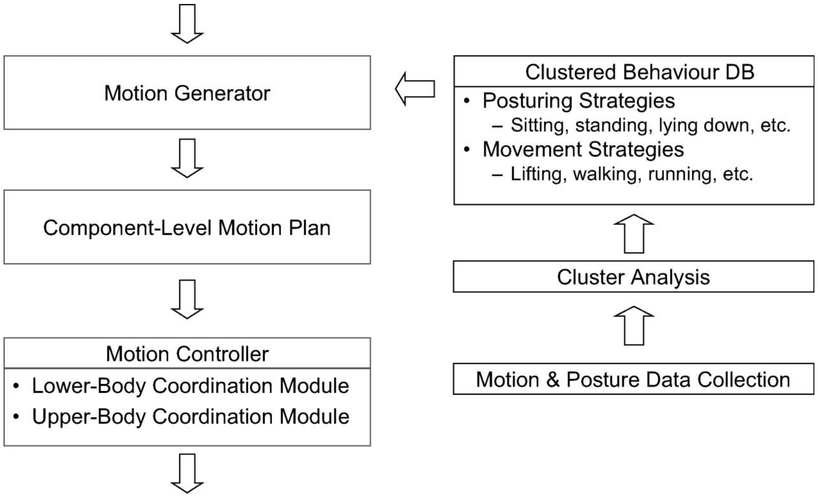

Figure 6. A generalised integrative framework for strategy-based motion simulation. Components of the Reed *et al.*, 2006) model are shown on the left, with recommended new components on the right. DB = database.

former authors suggested that these unbalanced postures were adopted to facilitate movement of the right foot for controlling pedals. They proposed an asymmetric design of the seat cushion area in contact with drivers' buttocks, in order to better support these leftward lean driving postures and ultimately to make the seat more comfortable for drivers. As such, when designing and assessing the driving workspace using DHMs, more sophisticated driving postures based on actual drivers' behaviours should be used in order to ensure valid design and evaluation.

Due to the exploratory nature of cluster analysis, the final number of clusters is somewhat arbitrarily chosen (Hair and Black 2000). As three postural strategies were determined by visually examining each clustered dendrogram (Figures 1 and 3), a different number of clusters can be selected. In both vehicle classes, the third cluster ('extended') was the most dissimilar (distal) to the other two and joined the remaining clusters last when a one-cluster solution is obtained at the end. If two clusters are desired (or two postural strategies), the two-cluster solution is 'flexed' and 'extended'. However, this 'flexed' strategy should be divided again into two groups when positioning DHMs, as the current results indicated that the first two clusters were mutually exclusive (i.e. one subgroup had their lower limb(s) flexed and the other subgroup had their upper limb(s) flexed, but neither group had both upper and lower limbs flexed at the same time). Therefore, the minimum number of postural strategies appears to be three, which was the choice in this study.

There are some potential limitations in the current study. Three postural strategies were identified for sedans and SUVs, but those for other vehicle classes (e.g. sports car, van, truck, bus) have not been investigated. Prior to cluster analysis, the perception-based data filtering procedure, described in Kyung (2008), to remove uncomfortable joint angles was not used. Hence, the postural strategies identified in this study do not necessarily represent 'comfortable' driving postures, but rather 'preferred' driving postures, which are more likely observed in current cars. In addition, driving postures were obtained after 20 min driving. Hence, it is necessary to explore whether long-term driving postures would be categorised into the same or similar postural strategies. It would also be interesting to investigate whether long-term driving postures can be categorised into static and dynamic sitting strategies, which were previously identified among 2-h seated office workers (Beach *et al.* 2005).

5. Conclusions

Three postural strategies were identified for two vehicle classes and represent three distinct interactive techniques used by drivers. These findings are expected to facilitate improved DHM-based driver workspace design and evaluation and to increase accuracy in prediction of driving postures. To further generalise the findings of the current study, larger-scale investigation is warranted to address more diversity in terms of ethnicity, vehicle class and driving duration. The strategy-based motion-classification method described in this study can be expected to be of use in other contexts, such as when predicting more complex human motions for ingress/egress, reaching and manual material handling.

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