A 3-D analysis of the joint torques developed during driver's Ingress-Egress motion

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Abstract

Providing an easy ingress-egress movement (I/E) remains a challenge for car designers. I/E has been largely studied in kinematics, but not in dynamics. This study proposes: 1/ to evaluate and describe the motor torques developed in the lower limbs and lumbar joints during I/E motions and 2/ to analyse the influence of the car geometry and subject anthropometry.

An experiment was performed to observe 15 subjects of three anthropometrical groups getting in and out of a car mock-up simulating three different vehicle configurations. Motor torques were extracted using an inverse dynamics analysis.

Both ingress and egress motions were primarily characterized by large torques. Overall, the taller a subject and the lower the seat of the vehicle were, the larger the peak torques were. Moreover, peak torques were higher for egress than ingress. These results are discussed in regards of the current knowledge on I/E ergonomics.
Car ingress-egress (I/E) is an ergonomics challenge. Little is known about the physical efforts developed in this motion. Developed motor torques were experimentally assessed for three anthropometrical groups and vehicle configurations. Results obtained were discussed in regards of the current knowledge on I/E ergonomics.
Keywords

Ingress-Egress

Joint torques

3D Human motion analysis

Biomechanics

Digital Human Model
A 3-D analysis of the joint torques developed during driver's Ingress-Egress motion

Introduction

Vehicle accessibility is a major ergonomics challenge for car manufacturers: vehicles should be designed so that driver and passengers are able to easily get in and out of them. However, ingress-egress (I/E) involves complex whole body motions in a highly constrained environment dealing with equilibrium constraints. It may also imply high physical efforts. Not surprisingly I/E movements were identified as a particularly difficult task by 25% (ingress) to 33% (egress) of elderly drivers (Herriotts, 2005).

Many researches were dedicated to describe both this motion and the influence of parameters related to the subject and the vehicle's characteristics on this motion. Experimental studies focused on identifying the intrinsic (anthropometry, functional capacities…) and extrinsic (e.g. car geometry) parameters associated with I/E difficulties (Giacomin and Quattroccolo, 1997; James, 1985; Petzäll, 1995). Though these studies are useful for improving vehicle design, they did not quantify the motion in terms of biomechanical quantities, and thus did not allow a better understanding of possible causes of the difficulties encountered by subjects. Recently, a few investigations were performed trying to relate I/E discomfort with biomechanical parameters (Andreoni et al., 2004 and Causse et al., 2012). But they focused only on a few specific kinematic parameters (the neck/torso kinematics). Complete and detailed descriptions of the 3-D kinematics have been proposed, notably by Chateauroux and Wang (2010) and Ait El Menceur et al. (2008) who identified different kinematic strategies used by volunteer subjects. Regarding the dynamics, a preliminary analysis of the left hip abduction torque for one subject can be found in (Debril et al., 2007). Causse et al. (2009)
presented a preliminary study showing the feasibility of the joint loads estimation for the I/E motions. However a complete description of the joint loads observed during car I/E motions is still missing.

In order to fill this gap, we propose in this study: 1/ to estimate and describe the joint torques developed during driver’s ingress-egress motions and 2/ to analyse the influence of the car geometry and subject anthropometry on the torques developed.

**Materials and Methods**

**Experiments**

The data was extracted from a larger experiment published in Causse et al (2012). Main features of experimental conditions are recalled here.

The motions of 15 young volunteers were analysed in this study. The subjects were free from any disabilities and were regular drivers. Subjects were spread in three groups of five according to their stature: Short (S), Medium (M) or Tall (T) (see Table 1).

An adjustable mock-up was used to represent the car (see Figure 1). It consisted of a seat, a steering wheel, pedals, a door frame and a door. Three car configurations were simulated, according to seat height (see Table 2): a small car (V_S), a medium-sized car (V_M) and a minivan (V_V).

For each car configuration, subjects were asked to get into the car mock-up and adopt a driving posture for five seconds before getting out of the car and moving away from the door frame. Subjects were also instructed not to use the door, kept open at 70°.

The mock-up was equipped with four 6-D forces sensors: two Bertec® force plates embedded in the car floor under the steering wheel and in the laboratory ground next to the doorframe, a specific force plate located under the seat and a load sensor (Denton®) behind the steering wheel (see Figure 1). In addition, subjects were equipped with 44 reflective
markers – among which 34 are located on specific anatomical bony landmarks -, whose
trajectories were recorded at 100 Hz using a 10 cameras optoelectronic system (Vicon® MX).

**Data processing**

Ingress motions started when the right foot left the ground moving into the car and ended
when the left foot touched the floor. Egress motions were defined between the instant when
the left foot left the floor and the instant when the right foot touched the ground. Start and
stop times were estimated from the vertical kinematics of the feet.

Joint angles were estimated using a motion reconstruction procedure similar to the one
described in (Wang et al., 2005). At first the Digital Human Model (DHM) Ramsis was
tailored to the subject using a set of anthropometric dimensions and the Bodybuilder module
of Ramsis. This personalized DHM was then exported to the RPx software (internal tool
developed between IFSTTAR and Renault) and superimposed to at least two calibrated
pictures of the subject taken from different points of view. It allowed a finer adjustment of the
body dimensions and attachment of markers in the local coordinate systems of the segments.
Then joint angles were estimated at each frame of the motion using a global optimization
procedure including coordination laws for the spine (Monnier et al., 2007). The optimization
procedure was initialized at each frame by a referential posture. This posture was defined
using an interpolation between a standard standing posture and a standard seated posture for
the ingress motion, and conversely for the egress motion. The kinematic linkage, based on the
Ramsis digital manikin, was made of 25 segments, linked by 25 joints and 64 degrees of
freedom (the sight of view and the fingers were not considered, see Figure 2.A). The accuracy
of the motion reconstruction procedure was assessed by visual inspection and by analysing the
residual distances between markers attached to the model and their measured positions.

A standard inverse dynamics procedure was used to compute the net joint torques
(NJT) developed in the lower limb and lumbar joint during these motions (Monnier et al.,
2009). The procedure was based on a Newton-Euler recursive approach developed by (Doriot and Chèze, 2004). The body was segmented in 16 rigid bodies according to the kinematic model, except for the feet, merged in a single segment, and the trunk, represented by only two segments, namely the abdomen and thorax (see Figure 2.B). The 3-D inertial parameters of these 16 rigid bodies were estimated from regressions based on anthropometric measures (Dumas et al., 2007). Different recursive strategies could be used to calculate the net joint loads (forces and moments). Results reported in this study were obtained using a “going-up” strategy, from the feet up to the lumbar joint. However, loads acting in the lumbar joints were also computed using a “going-down” strategy, from the upper extremities down to the lumbar joints. Differences between the results of these two strategies provide an estimation of the accuracy of the procedure (Robert et al. 2007). For each of the six components of the lumbar net joint wrench (three forces and three torques), RMS differences between “going-up” and “going-down” net joint loads were computed and normalized by the highest amplitude between the two strategies.

According to Desroches et al. (2010), the motor torques (MT) were computed by projecting the NJT orthogonally onto the mobility axes, i.e. the axes of the non-orthogonal Joint Coordinate Systems, defined according to ISB's standard (Wu et al. 2002).

To be able to compare trials of different durations, MT were resampled over 101 frames (0 to 100 % of the motion). Normalized motor torques (MT$_{\text{norm}}$) were then computed by divided the MT by subject’s stature and weight as proposed by Hof (1996). This normalization was used to cancel the anthropometrical effects from the torque values (the heavier or the longer the segment, the larger the joint torques) and thus to investigate how subjects from different anthropometry performed the task (see Discussion). In order to facilitate the interpretation of these MT$_{\text{norm}}$, Table 3 displays both the maximum MT that can
be developed by an average male for each degrees of freedom, and the corresponding MT$_{\text{norm}}$
considering a 50th centile male anthropometry (75 kg, 1.75 m).

Peaks of MT$_{\text{norm}}$ were extracted for each trial and the most characteristic degrees of
freedom (see section Results). Influence of subject's anthropometry and vehicle's dimensions
on these peaks was evaluated using an ANOVA with factors Stature ("S", "M", "T") and
Vehicle configuration ("V_S", "V_M", "V_V").

An overall comparison of peak MT$_{\text{norm}}$ between ingress and egress was performed
using a paired-sample t-test procedure. It included the peak torques that were comparable
between the two motions, i.e. the peak extension torques for the left knee, right knee, left hip
and lumbar joint, the peak torques in external rotation for the right hip and the peak right
bending torque for the lumbar joint, for every subject and the three vehicle configurations.

Results

General overview

Forty-five Ingress and Egress motions (3 vehicles configuration for 15 subjects) were
reconstructed and analysed. An example of reconstructed kinematics is given in Figure 3.

RMS values of the residual distances between markers attached to the model and their
measured positions, averaged across trials, subject and markers, was 10 mm with a standard
deviation of 5 mm. Comparison of the lumbar net joint forces and torques computed from two
different recursive strategies (bottom-up or top-down) is given in Table 4. The normalized
RMS ranged between 10% and 20%, which are typical values for this type of analysis
(Monnier et al., 2009; Causse 2001).

All participants went in and out of the vehicle using the "one foot" strategy (Ait El
Menceur et al., 2008; Chateauroux and Wang, 2010), as displayed in Figure 3. In some cases,
different sub-strategies were observed. For example, according to the definitions proposed by
Ait El Menceur et al. (2008), three subjects from the "Medium" group got into the car using the backward motion sub-strategy (entered with the pelvis first, lumbar flexed, and then rotated), while the two others used the lateral sliding sub-strategy (entered lumbar bent, and slid laterally into the car; see Figure 4). However, there is a continuous transition between these sub-strategies, and it is difficult to distinguish them. In addition, the observed motions and joint torque profiles were, overall, relatively stereotypical. Consequently, it was decided to present the results per group of subject and type of vehicle, regardless of the sub-strategies.

**Influence of the torques normalization**

Influence of the torques normalization by subject’s stature and weight is highlighted in Figure 5. It displayed the peaks of both MT (left panel) and MT$_{\text{norm}}$ (right panel) for the right knee flexion during Ingress for the three groups of subjects (averaged across subjects and vehicle configurations ± one standard deviation). One can observe that MT developed by the Short subjects were lower than those developed by Medium and Tall subjects (Figure 5.A). However, the opposite is observed on MT$_{\text{norm}}$, which are smaller for the Tall subjects (Figure 5.B, see also Table 5).

**Description of the joint torque developed during the Ingress motions**

Figure 6.A provides an example of the MT$_{\text{norm}}$ time profiles (mean and standard deviation across subjects) developed by subjects of the "Medium" group while entering the medium-sized vehicle configuration ($V_M$). The general shape of the time profiles for other groups and vehicle configurations are very similar, and the following description applies to the nine tested conditions (3 groups of subject, 3 vehicles configurations). In every case, three main phases, of about equal duration, can be identified.

At first, subjects entered their right foot into the car. It implied small flexion and abduction torques in the right hip. The right foot being in the air, abduction torque in the left
hip is needed to support the pelvis, similarly to what is observed in the support leg during the stance phase in gait (Eng and Winter, 1995; Doriot and Chèze, 2004).

Then, during about the second third of the motion, subjects translated and lowered their pelvis into the seat and moved their torso inside. This phase was mainly characterized by large extension torques in the lower limb joints, and in a lesser part by external rotation torque in the hips, to control the lowering of the pelvis. In order to avoid the collision with the roof, the torso had to be maintained bent laterally and flexed, leading to extension and rightward bending torques in the lumbar joint. Note that the bending torques appeared during the first phase, i.e. while the right foot was being placed into the car.

The third phase consisted in moving the left leg into the car, i.e. moving it above the sill. It is characterized by high left hip flexion torque required for moving the left leg in the air, and a leftward bending torque of the lumbar joint. This later tended to tilt the pelvis rightward and to help raising the hip (and thus the left leg).

**Description of the joint torque developed during the Egress motions**

Similarly to Ingress motions, the $MT_{\text{norm}}$ (mean and standard deviation across subjects) developed by subjects of the "Medium" group while exiting the $V_M$ vehicle configuration are displayed in Figure 6.B. The time profiles of the joint torques present similar overall shapes for other groups of subjects and vehicle configuration. As in the previous section, the following results are shared between all tested configurations, and are not specific to the one displayed in Figure 6.B.

Egress motion can be divided in two main phases of about equal duration. The beginning of the motion was characterized by the transport of the left leg outside the vehicle and the rotation/transfer of the body to the left. In terms of joint torques it implied: 1/ flexion torque in the left hip for moving the left foot above the sill; 2/ Slight internal rotation,
abduction torques and extension torques in the right hip, corresponding to the body rotation and transfer to the left by the right leg.

The second phase was characterized by large torques necessary for raising the body, in particular peaks of extension torques in both knees, and the left hip. They were similar to those observed in Sit-to-Stand motions (Bahrami et al., 2000). Due to its posture (see Figure 3), the right hip is more loaded in axial rotation (external rotation) than extension. The trunk has to be bent forward and to the left in order to pass under the roof, resulting in extension and rightward bending torques in the lumbar joint.

In their kinematic description of egress motions, Chateauroux and Wang (2010) identified a third phase corresponding to the motion of the right foot over the sill. However it could not be identified from MT_{norm} curves. The end of the motion, i.e. when it is comparable to a stance phase of gait, is only characterized by abduction torque in the left hip, similar to the beginning of the ingress motion.

**Influence of the stature and vehicle**

Tables 5 and 6 display the main peaks of MT_{norm}, averaged across subjects for each vehicle configuration and anthropometric group, for different phases described in the previous section and for ingress and egress motions respectively. These tables also summarize the ANOVA results with factors Stature (3 modalities for the three groups of subjects "S", "M" and "T") and Vehicle (3 modalities for the three vehicle configurations "V_S", "V_M" and "V_V") performed on these peaks of MT_{norm}.

Influence of these two factors was mainly observed during the second phase of both ingress and egress motions (lowering of the pelvis for the ingress, rising up for the egress). During this phase, higher MT_{norm} were observed for lower seat height vehicle configurations and taller subjects. Two exceptions can be noticed for the ingress motions (see Discussion): effect of Stature on the right knee extension (taller subjects developed smaller MT_{norm} than
Influence of Stature and Vehicle on the \( M_{\text{norm}} \) during the other phases was smaller. The only significant effect is observed during the first phase of the egress motion for the right hip abduction and internal rotation: the taller the subjects and the lower the vehicle’s seat were, the smaller the \( M_{\text{norm}} \) were.

**Difference between Ingress and Egress peak torques**

Peaks of \( M_{\text{norm}} \) were compared between ingress and egress motions for the following degrees of freedom: extension for the left knee, the right knee, the left hip and the lumbar joint, external rotation for the right hip and right bending for the lumbar joint. Figure 7 shows these peak values for ingress and egress, averaged across subject and vehicle’s configurations, plus and minus one standard deviation. A paired-sample t-test was performed considering all these degrees of freedom between ingress and egress. It showed that, overall, peak of \( M_{\text{norm}} \) were larger for egress than ingress (\( p<0.001 \)).

**Discussion**

**Accuracy of the data processing**

This study proposed a quantified description of the motor torques developed during ingress and egress motions. These data were obtained through a succession of processing, each of them relying on only partly satisfied assumptions and imperfect input data. This resulted in potential inaccuracies in the results.

Joint angles may be affected by several factors such as: an incorrect adjustment of the DHM (in particular its kinematic linkage) onto each specific subject; an incorrect positioning of the skin markers in the local coordinate system of the segments; soft tissue artefacts leading
to motion of markers relative to the rigid bony structure. As a consequence, residual distances between the model’s markers and their measured location remained small: mean RMS value of 10 ± 5 mm comparable to results from previous studies (Wang et al., 2005). These values are within the range of inter/intra observer repeatability in positioning anatomical landmarks (Croce et al., 2005).

Sensitivity of the joint torques estimated with an inverse dynamics procedure to the kinematic data and their filtering, the estimated body segment inertial parameters or the position of the contact forces has been documented (Holden and Stanhope, 1998; Silva and Ambrosio, 2004; Rao et al., 2006; Robert 2006; Ren et al., 2008). As a result, differences were observed between the lumbar joint loads obtained with the bottom-up or top-down strategy (see Table 4). These later values are typical from those of our previous studies (Monnier et al., 2009; Causse 2001), and should be considered when analysing the results of this study.

**Overall motion description**

Analysis of the torque profiles allowed identifying different phases in these motions. These phases could be linked to those proposed in the kinematic descriptions of the I/E motions (Chateauroux and Wang, 2010). This could be explained by the fact that the studied I/E motions were relatively slow. Joint torques were therefore primarily due to the gravity and thus driven by subject’s postures.

Although subjects used different sub-strategies, the resulting joint torques for a given configuration (group of subjects and vehicle) were, overall, relatively stereotypical. Both ingress and egress motions were primarily characterized by large extension torques corresponding to the seating/rising phase. On the opposite, joint torques during the initial phase (moving the right foot inside / the left foot outside) and terminal phase (moving in the right foot / moving out the left foot) were more specific to ingress or egress.
Motor Torques vs. Normalized Motor Torques

In this study we chose to analyze the Normalized Motor Torques ($MT_{\text{norm}}$), i.e. the motor torques ($MT$) normalized by subject’s stature and weight. This normalization being performed for each subject, it does not affect the within subject effects, in this case the effect of the car geometry. However, between-subject effects, in this case the effect of the anthropometrical group, on MT or $MT_{\text{norm}}$ are different (see Figure 5). Influence of the anthropometrical group on the $MT_{\text{norm}}$ underlined the differences in the way that subjects from different statures get in and out of a vehicle.

Effects of Vehicle and Stature

During the rising/seating phase, the car geometry had almost systematically the same effect on the peak $MT_{\text{norm}}$: minivan ($V_V$) induced lower $MT_{\text{norm}}$ than two other vehicle configurations ($V_M$ and $V_S$). The decrease in extension $MT_{\text{norm}}$ may be directly linked to the increase of the seat height, as already observed in Sit-to-Stand motions for example (Su et al., 1998).

A similar effect was found for the Stature: taller subjects tended to develop larger $MT_{\text{norm}}$. As stated above (see previous paragraph) effects of Stature underlined the different interactions between subjects with different anthropometries and vehicles with fixed dimensions (in particular the seat height): a same seat height is relatively lower for taller subjects than for shorter persons. A notable exception is the influence of Stature on the right knee extension for ingress motion: taller subjects developed smaller $MT_{\text{norm}}$ than other groups. It could be explained by the fact that taller subjects used the steering wheel more frequently and more intensively during this lowering phase (Causse, 2011), thus reducing the torques in the right lower limb.
Consequences of interactions with other parts of the vehicle are more complex. In particular, subjects may adapt their motion (use a different sub-strategy) when the constraints (e.g. the roof clearance) become too strong. For example, subjects have to bend and flex their trunk while entering the car to avoid collision with the roof. For low seat height vehicles, with lower roof height, one may expect that subjects will increase both trunk flexion and lateral bending, leading to larger lumbar $MT_{\text{norm}}$. However, the opposite was observed for the bending $MT_{\text{norm}}$: it was smaller for lower seat configuration vehicles (see Table 5). A kinematic analysis performed in a previous study (Causse et al, 2012) showed that subjects tended to be more rotated to the left while entering vehicles with lower seat, thus limiting the bending.

**Link with ergonomics evaluation**

Evaluation of the difficulties encountered by the subjects during ingress/egress tasks was not the main topic of this study. Rather, this study focused on the motor torques developed during I/E motions. Nevertheless, as they are linked to the muscular efforts produced during the motion, one may expect that they are related to the difficulty perceived during the motion. Consequently the results of this study can be discussed in regards of existing findings about ingress/egress discomfort.

Peak torque values observed in this study could be compared to the maximum values reported in the literature for young male (see Table 3). Motor torques developed (both $MT$ and $MT_{\text{norm}}$) were up to 50% of the maximal average static strength of young males for most of the joints. It highlights the potential difficulties encountered during this motion, in particular by people with reduced physical capacities such as the elderly (Herriotts, 2005).

It also appeared that car configurations with a higher seat induce lower torques. It can be related to previous studies showing that getting in and out is easier for minivans than for smaller cars (Causse, 2011). Similarly, peak joint torques developed during egress were
overall larger than during ingress. This is in agreement with the results from Herriotts (2005) showing that egress is found more difficult than ingress, in particular for older drivers.

Nonetheless, motor torques by themselves cannot explain all the difficulties encountered by the subjects. As an example, moving the left foot in (the right foot out) the vehicle during ingress (egress) was specifically mentioned as a difficulty by Herriotts (2005). Yet, the corresponding values MT or MT$_{\text{norm}}$ observed in this study remained small, i.e. far from the maximum values reported in Table 3. An explanation may be that the maximal force production capacities reported in Table 3 are independent of the posture. However, this postural effect can be substantial, in particular close to the joint limits (Chaffin et al., 2006; Delp, 1990), and neglecting it may lead to inaccurate analyses. A musculoskeletal model may be interesting to overcome this limitation. Another plausible explanation could be that the causes of the discomfort are not the effort to produce, but rather the proximity to the kinematic joint limits (Cruse et al., 1990; Kee and Karwowski, 2001), other kinetic components such as passive torques or net forces (Keeley et al., 2012), or collision with parts of the vehicle, e.g. too width sill (Causse et al. 2012).

Limitations

Several potential limitations were already discussed in the previous sections, such as the potential inaccuracies introduced by the data or the fact that a global description was presented without finely considering all sub-strategies employed by the. However, additional limitations should be mentioned.

Some are related to the classical inverse dynamics method use in this study. In particular, it requires the measurement of all contact loads between the subject and its environment. It implies a large experimental effort to equip as many mock-up parts as possible with load sensors. However, one cannot handle all possible contact situations. Typically, in this study, the door was not equipped and subjects were instructed not to use it.
It surely limited the variety of I/E strategies. In addition, subject may have several segments in contact with the same equipped part leading to closed-loop problems. In such case, joint torques in the closed-loop are indeterminate (Vaughan et al., 1982). For instance, several subjects had both hand on the steering wheel during part of the motion. In these cases, upper limb joint could not be estimated with the classical inverse dynamics method used in this study. Alternative inverse dynamics approaches (e.g. Robert et al., 2013) may help but should be used with caution.

Other limitations come from the difficulty to extend the experimental results of this study beyond the specific situation studied (I/E of young drivers). In particular, results of this study could not be directly transferred to the other car occupants as the interactions with the vehicle are likely different for drivers, front row passengers or a second row passengers: more or less space available, possible grasp location for the hands (steering wheel for the driver, seat back for the second row occupants), etc. Although one can expect that some characteristics observed for the driver, such as the large extension torques during seating/rising phase, should also be observed for the other occupants, specific studies should be performed on the other occupants. Another issue is that the presented results were obtained on young healthy volunteers, although they are not the population for which I/E is the most critical. It would thus be interesting to extend the current study by studying alternative populations such as elderly.

**Conclusion**

This study proposes the first description of the motor torques (i.e. the net joint torques projected on the mobility axes) developed during driver’s ingress-egress motions. They were stereotypical across subjects and conditions. Both ingress and egress motions were primarily characterized by large extension torques corresponding to the seating/rising phase. These torques are similar to those observed in Sit-to-Stand manoeuvres.
In this study, we also analyse the influence of the car geometry and subject anthropometry on the normalized motor torques $MT_{\text{norm}}$ (motor torques normalized by the subject’s stature and weight). In general, the taller the subject and the smaller the vehicle are, the larger the peak $MT_{\text{norm}}$ are. Moreover, peak $MT_{\text{norm}}$ were overall higher for egress than ingress. These results could be related to previous studies showing that getting in and out is easier for minivans than for smaller cars, and that egress is more difficult than ingress.

Acknowledgments
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International Digital Human Modeling Symposium, 11-13 June 2013, Ann Arbor (USA).
International Symposium on the 3D Analysis of Human Movement, 18-20 July, Bologna (Italy).

References


Table 1. Characteristics of the three groups of subjects.

<table>
<thead>
<tr>
<th>Group</th>
<th>Stature (m)</th>
<th>Weight (kg)</th>
<th>Age</th>
<th>Gender</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short (S)</td>
<td>1.59</td>
<td>51.0</td>
<td>28.4</td>
<td>5 F*</td>
</tr>
<tr>
<td></td>
<td>(1.57 – 1.61)</td>
<td>(41.6 – 56.8)</td>
<td>(26 - 32)</td>
<td></td>
</tr>
<tr>
<td>Medium (M)</td>
<td>1.68</td>
<td>63.8</td>
<td>25.8</td>
<td>2 F – 3 M**</td>
</tr>
<tr>
<td></td>
<td>(1.63 – 1.75)</td>
<td>(53.7 – 80.3)</td>
<td>(23 - 29)</td>
<td></td>
</tr>
<tr>
<td>Tall (T)</td>
<td>1.85</td>
<td>74.2</td>
<td>29.2</td>
<td>5 M</td>
</tr>
<tr>
<td></td>
<td>(1.81 – 1.87)</td>
<td>(66.2 – 82.0)</td>
<td>(21 - 36)</td>
<td></td>
</tr>
</tbody>
</table>

*Female, **Male
Table 2. Main dimensions (in mm) of the three car configurations: small ($V_S$), medium ($V_M$) and minivan ($V_V$). See Causse et al. (2012) for further details.

<table>
<thead>
<tr>
<th></th>
<th>$V_S$</th>
<th>$V_M$</th>
<th>$V_V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seat height above ground (1/H5)*</td>
<td>470</td>
<td>550</td>
<td>700</td>
</tr>
<tr>
<td>Seat height above floor (2/H30)</td>
<td>240</td>
<td>290</td>
<td>350</td>
</tr>
<tr>
<td>Sill height above ground (3/H130)</td>
<td>360</td>
<td>360</td>
<td>420</td>
</tr>
<tr>
<td>Doorway width (4+7/-)</td>
<td>1050</td>
<td>950</td>
<td>950</td>
</tr>
<tr>
<td>Roof height (1+5/-)</td>
<td>1230</td>
<td>1330</td>
<td>1500</td>
</tr>
</tbody>
</table>

*: figures in brackets indicate the corresponding measure in Causse et al. (2012) / the similar definition by SAE J1100 (2009)
Table 3. Maximal Motor Torques (MT) that can be developed by average males for different degrees of freedom according to the literature and their corresponding normalized Motor Torques (MT\text{\text{norm}}) considering a 50\text{th} centile male (75 kg, 1.75 m).

<table>
<thead>
<tr>
<th>Joint</th>
<th>DoF</th>
<th>Maximum torque capacity</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MT (N.m)</td>
<td>MT_\text{norm} (n.u)</td>
</tr>
<tr>
<td>Knee</td>
<td>Flex. / Ext.</td>
<td>130</td>
<td>0.101</td>
</tr>
<tr>
<td>Hip</td>
<td>Flex. / Ext.</td>
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<td>0.144</td>
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<td>Abd. / Add.</td>
<td>120</td>
<td>0.093</td>
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<td>Int. / Ext. Rot.</td>
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<td>0.047</td>
</tr>
<tr>
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<td>Flex. / Ext.</td>
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<td>0.148</td>
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<tr>
<td></td>
<td>Right / Left Bend.</td>
<td>160</td>
<td>0.124</td>
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<tr>
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<td>Right / Left Ax. Rot.</td>
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Table 4. RMS and normalised RMS (RMS\%) differences between the lumbar net joint loads computed from the “going-up” and “going-down” strategies averaged across subjects and trials (standard deviation in small italics). Loads are expressed in a coordinate system paralell to the SAEJ100 vehicle coordinate system centered at the lumbar joint. RMS values are expressed in N or N.m for the forces and torques respectively, while RMS\% are unitless.

<table>
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<th></th>
<th>Fx</th>
<th>Fy</th>
<th>Fz</th>
<th>Mx</th>
<th>My</th>
<th>Mz</th>
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<tr>
<td>RMS%</td>
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<td>13</td>
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<td>11</td>
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<tr>
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<td>33</td>
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<tr>
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<td>13</td>
<td>4</td>
<td>16</td>
<td>4</td>
<td>18</td>
<td>5</td>
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Table 5. Peaks of normalized motor torque $MT_{\text{norm}}$, multiply by $10^3$ for a better readability, for the main degrees of freedom for the Ingress motions averaged across subjects for each vehicle configuration ($V_S, V_M, V_V$) and anthropometric group (S, M and T) (standard deviation in small italics). Last column displays the effects of factors Stature and Vehicle (only the significant effects are reported).

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<thead>
<tr>
<th>Phase</th>
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<th>M</th>
<th>T</th>
<th>S</th>
<th>M</th>
<th>T</th>
<th>S</th>
<th>M</th>
<th>T</th>
<th>S</th>
<th>M</th>
<th>T</th>
<th>Stature</th>
<th>Vehicle</th>
<th>Sig. effects and groups*</th>
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<td>14.1</td>
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<td>V_V&lt;(VS,VM)</td>
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<tr>
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</table>

*($p<0.05$)

$S, M$ and $T$ stand for the three levels of the factor Stature (Short, Medium and Tall respectively)

$V_S, V_M, V_V$ stand for the three levels of the factor Vehicle configuration (Small car, Medium size car and Minivan respectively)
Table 6. Peaks of normalized motor torque $MT_{norm}$, multiply by $10^3$ for a better readability, for the main degrees of freedom for the Egress motions averaged across subjects for each vehicle configuration ($V_S$, $V_M$, $V_V$) and anthropometric group (S, M and T) (standard deviation in small italics). Last column displays the effects of factors Stature and Vehicle (only the significant effects are reported).

<table>
<thead>
<tr>
<th>Phase</th>
<th>Joint</th>
<th>Axe</th>
<th>Small car $V_S$</th>
<th>Medium size $V_M$</th>
<th>Minivan $V_V$</th>
<th>Sig. effects and groups*</th>
</tr>
</thead>
<tbody>
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<td></td>
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<td>M</td>
<td>T</td>
<td>S</td>
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<tr>
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<td>70.6</td>
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</table>
|       | R. Bend.| 30.3  | 7.2   | 46.1  | 14.2  | 33.5  | 13.4  | 34.0  | 8.6   | 36.7  | 15.4  | 31.5  | 7.7   | 34.5  | 7.7   | 47.1  | 18.3  | 33.4  | 30.3  |*<p<0.05*

*S, M and T stand for the three levels of the factor Stature (Short, Medium and tall respectively)

$V_S$, $V_M$, $V_V$ stand for the three levels of the factor Vehicle configuration (Small car, Medium size car and Minivan respectively)
Figure 1. 3D representation and picture of the adjustable car mock-up.
Figure 2: The DHM used in this study, with A/ its kinematic linkage; B/ the dynamic segmentation.
Figure 3. Example of reconstructed ingress and egress motions.
Figure 4. Illustration of the two sub-strategies used by subjects of the "medium" group when moving into the car. A/ backward motion sub-strategy; B/ lateral sliding sub-strategy.
Figure 5. Peaks of right knee flexion torque during Ingress for the three groups of subjects (averaged across subjects and vehicle configurations ± one standard deviation; stars indicate significant differences at a p-level of 0.05): A/ motor torques (MT); B/ motor torques normalized by subject’s stature and weight (MT_{norm}).
Figure 6. Normalized motor torques $MT_{\text{norm}}$ (net joint torques projected on mobility axes and normalized by subject’s stature and weight) developed by the "medium" group of subjects and the $V_M$ vehicle configuration ("medium-sized car"), averaged (thick line) ± one standard deviation (shaded area) across subjects. A/ Ingress motion; B/ Egress motion. Figures represent the peak of motor torques (MT) considering a $50^{\text{th}}$ centile male (75 kg, 1.75 m).
Ingress
Egress
Figure 7. Comparison of peaks of normalized motor torques $MT_{\text{norm}}$ (average across subjects and configurations ± one standard deviation) developed during Ingress (white bars) and Egress (black bars) motions. Only peak torques comparable between the two motions and used in the paired sample t-test (see section Data Analysis) are displayed.