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The contribution of seat components to seat hardness and the interface between human occupant and a driver seat

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Abstract: Effective digital human model (DHM) simulation of automotive driver packaging ergonomics, safety and comfort depends on accurate modelling of occupant posture, which is strongly related to the mechanical interaction between human body soft tissue and flexible seat components. This paper comprises: a study investigating the component mechanical behaviour of a spring-suspended, production level seat when indented by SAE J826 type, human thigh-buttock model hard shell; a model of seated human buttock shape for improved indenter design using a multivariate representation of Australian population thigh-buttock anthropometry; and a finite-element study simulating the deflection of seat cushion foam, underlying suspension and the seat frame when loaded by a 95th percentile occupant. The results of the three studies provide a description of the mechanical properties of the driver-seat interface, and allow validation of future dynamic simulations, involving multi-body and finite-element (FE) DHM in virtual ergonomic studies.

Keywords: digital human model (DHM); anthropometry; driver posture; automotive ergonomics; driver seat; seat design; foam deflection; meat-to-metal; virtual ergonomics; seat comfort; seat pressure; finite-element-model (FEM); seat suspension.

Biographical notes:

Gunther Paul has studied Engineering and Ergonomics at TU Darmstadt in Germany, where he received a Masters degree in Mechatronics and a PhD in Ergonomics. After working in research and academic teaching at TU Darmstadt for five years, he joined a leading global OEM in the automotive industry in 1999. He remained in product development, information technology and manufacturing engineering functions in the automotive industry in Germany and France until 2009. Gunther then moved to Australia, where he established a laboratory and research group in Ergonomics at the University of South Australia, funded by the automotive industry's collaborative research centre (AutoCRC). He is now Senior Lecturer for Occupational Safety, Health and Ergonomics at Queensland University of Technology. Gunther is co-chairing the IEA technical committee for human simulation and virtual environments and is specializing in biomechanical, digital human modeling.

Jon Pendlebury holds a BEng (Hons) in Engineering Design & Technology from Warwick University, UK, and a PgDip, MA in Industrial Design from the University of Central England, UK. Since graduating from University in 1994, he has been employed by Ford of Europe and Ford of Australia since 2006. Jon has moved roles through the entire Product Development process, from Plant Vehicle Teams in Genk, Belgium and Saarlouis, Germany focusing on cost and quality projects, a Tooling and Gauging Engineer in Dagenham Engine Plant to the many roles within Vehicle Engineering as a Package & Ergonomics Engineer, Integration Engineer and most recently in Basic Design (Advanced Vehicle Concepts). He is a Six Sigma Black Belt candidate and nominated for the Global Henry Ford Presidents Award. Jon is currently the Engineering Lead for new vehicle concepts in the Asia Pacific Region.

Jason Miller has a 19 year career predominantly built around product engineering and project management in the automotive industry. Graduated from RMIT University with a Bachelors degree in Metallurgical Engineering (1992), and later a Master of Management (Technology) from Melbourne Business School (1999), he has expertise in powertrain technologies, friction materials, fuel handling systems, fuel cell technologies and automotive interiors. Jason is extensively involved in advanced development in Australia, Europe and USA with multiple patents filed in the above fields. Since 2005, Jason is Manager Advanced Development at Futuris Automotive, and a casual lecturer at RMIT for the Master of International Automotive Engineering program since 2008.

1 Introduction

Seat interface pressure

Seat safety functions and seat comfort are crucial attributes for designing a seat (Van Hoof, van Markwijk, and Verver, 2004), and quite often a tradeoff can be found, as for example anti-submarining performance vs. comfortable posture (Andreoni et al., 2002). To analyze posture as a key component of static comfort, physiologic methods, landmark coordinate measurements or pressure maps are employed. Pressure mapping as the standard method for investigating static comfort (Siefert, Pankoke, and Wölfel, 2008) at the seat body interface however has not always delivered useful results in the past. While Kyung and Nussbaum (2008) studied the associations between three subjective ratings (overall, comfort, and discomfort) and 36 measures describing driver–seat interface pressure, and reported correlations between (1) lower pressure ratios at the buttocks and higher pressure ratios at the upper and lower back, (2) balanced pressure between the bilateral buttocks, (3) balanced pressure between the lower and upper body and overall / comfort ratings (rather than discomfort ratings), Gyi and Porter (1999, p.99), when analysing the technique of interface pressure measurement found that a “clear, simple and consistent relationship between interface pressure and driving discomfort” could not be identified and Kolich, Seal, and Taboun (2004) reported that given the current state of technology, with impractical and obtrusive pressure sensors influencing the measurement, seat-interface pressure measures are difficult to establish, which was supported by Paul, Daniell, and Fraysse (2012). Porter, Gyi, and Tait (2003) later repeated that for three cars, no clear relationship was found between interface pressure data and reported discomfort. Despite these findings, Kolich and Taboun (2004) presented a multiple linear regression model relating seat interface pressure characteristics to occupant data and subjective perceptions of seat comfort to a comfort index, on the basis of reliable pressure measures.

Seat cushion models

It was further on found that a linear comfort model is not valid for a wider range of foam types, and now focusing on pressure beneath the ischial tuberosities, Ebe and Griffin (2001) presented a new model using two static comfort factors: ‘bottoming’ reflected by foam stiffness, and ‘foam hardness’ at low forces. Most importantly they pointed out that, a force-deflection curve and consequently foam stiffness obtained according to ISO 3386 is not representative of forces applied by a seated passenger, and 25% ILD hardness measured on a foam block according to ISO 2439, ranging between 120-285 N (foam density 43-65 kg/m^3), does not represent the hardness of a foam pad found in a seat. Polyurethane (PU) foam is typically the major constituent of automotive seat pads, and exhibits highly nonlinear behaviour under normal operating conditions. Efficient design requires not only an understanding, but also a good model of such foam behaviour (Widdle Jr., Bajaj, and Davies, 2004).

To further complicate analysis, formerly moulded PU stock seat foam has recently been replaced with multi-density slab foam, using variable pressure foaming, following optimization of the foam densities to reduce weight by approximately 15% without affecting the seat performance and comfort (Edwards et al., 2004). This foaming process also allows higher density (stiffer) foams at the side wings of seats in a single seat. In general, foam material is described in terms of its compressive stiffness and stress-strain response, and its non-linear behaviour can be modelled idealized as hyperelastic (e.g. in an Ogden model) and isotropic, or realistic and complex, as anisotropic and viscoelastic, considering time dependency and hysteresis effects (Mills, 2007). As the settling point determined through deformation of human body and car seat is paramount for establishing initial conditions for kinematic simulations (Bourdet and Willinger, 2006), it is surprising that in all studies so far, only the seat cushion foam is modelled, but not a flexible sub-frame response (e.g. Grujicic et al., 2009). McEvoy et al. (2004) explored the performance of two PU foam formulations, a high resilient vs. a low resilient foam. Placed into a full foam seat suspension, the low resilient foam showed minor improvement on paved roads but a vast dynamic comfort improvement on rough roads. Low resilient foams employ a different polyol molecular weight than high resilient foams, despite maintaining the same static properties density and firmness, which in this study were 55kg/m^3 and 22kg-f at 25% deflection. Again, the contribution of seat suspension was not measured. In another study, Murata et al. (2002) developed a high performance foam based on a high resilient foam. They applied JIS K6400 and reported a core density of 57 kg/m^3, 25% ILD of 254 N/314cm^2 (~0.008 N/mm^2), a static spring constant of 7.5 N/mm at 196N, a stress relaxation rate of 11.8%, hysteresis loss of 21.3%, airflow rate of 21.5 L/min and a resonance frequency at 3.6 Hz. Advanced viscoelastic foams with energy absorption properties are also used to improve safety performance (Schmitt, Muser, and Niederer, 2003). Given the complexity of foam modelling, the question needs to be asked as to whether simplified 3D-shell surface models could be used with decreased computational time and cost, in order to approximate the behaviour of the solid three-dimensional, nonlinear contraction and expansion behaviour of foam (Thiyagarajan, 2008).

It should be noted that the material property 'foam stiffness'

$$k = \frac{E}{t} \quad (1)$$

(where k: foam stiffness; E: Young's modulus; t: thickness of material) is called either 'foam hardness' when measured according to ISO 2439 (or indentation load deflection, ILD; where foams are compressed by a 200 mm diameter circular plate at 10 cm/min) or 'foam firmness' when measured according to ASTM D3574 (or indentation force deflection, IFD; in which a circular flat indenter of area A= 323 cm^2 presses on a slab of foam, typically of thickness 100 mm and area 500 mm by 500 mm, supported on a flat table, perforated with small holes to ease air flow). The 25% IFD result also does not necessarily correlate with the seating stiffness for true load application, as the foam can creep. Foam selection criteria are low resilience and creep, and testing with a buttock form is advised (Mills, 2007). To be compatible with human soft tissue, open cell foams of the order of 20 kPa are used in automotive seats. This coincides with findings by Paul (2004), where comfortable, local pressures of drivers were found at values between 5-14 kPa, measured at a seat height H30 (SAE J1100) of 300mm and independent of driving conditions in a simulated environment.

Seat design however depends on customer preferences. In Germany harder seats are used, with smaller static compression strains than in the UK. The Japanese market uses foams with high energy dissipation and moderate strength, and the North American market uses foams with low energy dissipation, while the European market is intermediate. In upscale car seats, the cushion often sits on a mechanical spring suspension. While in cheaper and lighter seats, the foam cushion provides the majority of the deflection and changes shape significantly under load, the force–deflection relationship of a suspended seat is more linear (Mills, 2007).

Human modeling

It is important for protective systems performance that reliable tools be used which are representative of humans, and a similar assumption can be made for comfort oriented human models. In general, those tools can be either multibody, or finite-element (FEM), or combined multibody-FEM models. Comfort oriented FEM models so far assume simplified linear load-deflection characteristics of thighs and buttocks (Hartung et al., 2004; Mergl et al., 2004), although it is known from safety related research that human soft-tissue behaves as a nonlinear viscoelastic, anisotropic and inhomogeneous material (Grujicic et al., 2009). To simplify mathematical modelling of a realistic mechanical response of human soft-tissue, Grujicic et al. (2009) assumed (a) initial isotropy, (b) local homogeneity and (c) time-invariant (i.e. non-viscoelastic) material behaviour, and used a Mooney–Rivlin hyperelastic material model. In a very detailed extension of the H-Model™, Konosu (2003) also stressed the importance of modelling the pelvic joints (sacroiliac joint, pubic symphysis) and strain rate dependency of pelvic components (e.g. tibial cartilage, sacro-iliac ligaments) for improved kinematics performance. In a synthesis of the THUMS and H-Model™ for vehicle crash simulation, Murakami et al. (2004) developed a model which represents an average US adult male in a driving posture. As physical geometry, mechanical characteristics and joint structures were replicated as precise as possible, the total number of nodes reached about 67,000 and the model has about 1,000 materials. As usual, parameters were derived from cadaver tests though, and although muscle-tendon function is included in the model, this provides opportunity for further development.

The comfort oriented 3D-FE-model developed by Mergl et al. (2004) consists of the thigh and pelvis of a 50th percentile male. It matches biomechanical properties (force-deflection curves) of the soft tissue determined from in-vivo indentation tests on human subjects. It was found that for the thigh and pelvis, Young's-module varied from knees to buttocks (E=0.01-0.03 N/mm^2). Soft tissue was modelled as a linear elastic isotropic material, with Poisson's ratio of 0.49 and a density of 1100 kg/m^3, which is significantly too high and physically impossible. Young's modulus was modelled in four regions, for knee proximity (E=0.01 N/mm^2), thigh (E=0.015 N/mm^2), anterior buttocks (E=0.02 N/mm^2) and posterior buttocks (E=0.03 N/mm^2). Somehow contrary to this model, Mills (2007) reported that thigh deformation, calculated by subtracting the foam deformation from a total deformation, was larger than foam deformation for forces exceeding 60 N, when the foam stiffness exceeded thigh stiffness. Both materials are non-linear, but the Poisson's ratio of foam is much lower than that of the thigh. For an average initial skin to femur distance estimated as about 70 mm, the maximum compressive strain in the thigh tissue, when the deflection is 40 mm, is about 57%. Another linear, isotropic FEM model of human buttocks, to predict the pressure distribution between occupant and seating surface, was developed by Verver et al. (2004), who showed that pressure distribution at the interface between human and seat strongly depends on variations in human flesh and seat cushion properties. Due to the considerable inter-subject variability of bone and muscle anatomy (Viceconti, 2003), it should be considered that models so far do not aim to model a representative human femur, but only one generic human femur.

Unlike FEM models, which are able to investigate both contact and the interaction between occupant and the seat, but require many parameters to be defined, an accurate meshing algorithm and lengthy computations, multibody models allow to monitor the three dimensional kinematic behaviour of a virtual dummy. They simulate different postures and model human body properties, requiring the definition of only a small set of parameters. Moreover, the interaction with a vehicle can be described using lumped parameters. As the computational demand is reasonable, multibody simulations can easily handle various percentiles of occupants. However, a multibody model cannot investigate pressure distribution (Pennestrì, Valentini, and Vita, 2005). In addition to soft tissue material parameters, the geometric shape of thighs and buttocks need to be considered in both physical and analytical models. Such a model, based on multibody techniques and arbitrary surfaces attached to rigid bodies, was developed by Verver et al. (2005).

Only one study was found (Tuttle, Barrett, and Gass, 2007) which investigated seated buttock contours of Australians. A contour measurement device was developed and used to measure buttock contours of senior Australian high-school students in five sitting postures. Buttock contours were quantified by constructing anterior–posterior (AP) and lateral profiles from which six discrete profile dimension measurements were made. AP and lateral profiles were found to have a consistent shape across all participants. Five out of six profile dimensions were significantly different between genders, with just one significantly different between sitting postures.

In summary,

- Seat interface pressure is difficult to measure reliably, and although simulations are on a promising pathway, models still require significant work to achieve a level of specification and confidence required for comfort predictions.
- Seat cushion models have reached a good level of detail and assurance for the foam component. The contribution of the seat suspension to its dynamic behaviour, and the interaction between foam and seat suspension, have not been dealt with so far.
- Human FE models still require significant work in all areas, especially validity (i.e. representation of a general population), material properties, and geometric properties.

2 Methods

This chapter describes the methods applied to

- identify the reaction parameters of a suspension type seat under human-like hard shell indentation;
- model human thigh and buttock geometry for a selected Australian population
- and simulate occupant-seat interaction in a finite-element model.

Suspension seat parameter identification

To measure force-deflection behaviour of a suspension type seat within industry specification (75mm), Ford engineering specification CETP 01.10-L-401 was applied. Measurements were taken at the Ford of Australia material testing laboratory in Geelong.
The indenter was mounted to the testing rig so that the loading centre of the indenter was at the centre of the swivel joint. A fibreglass SAE AM50 type buttock form (Ford engineering test procedure CETP-01.10-L401 for seat cushion hardness testing; 450mm (l) x 370mm (w)) was attached and suspended from the indenter so the upper surface of the form, at rest, was on a 10° inclination from horizontal (Figure 1).

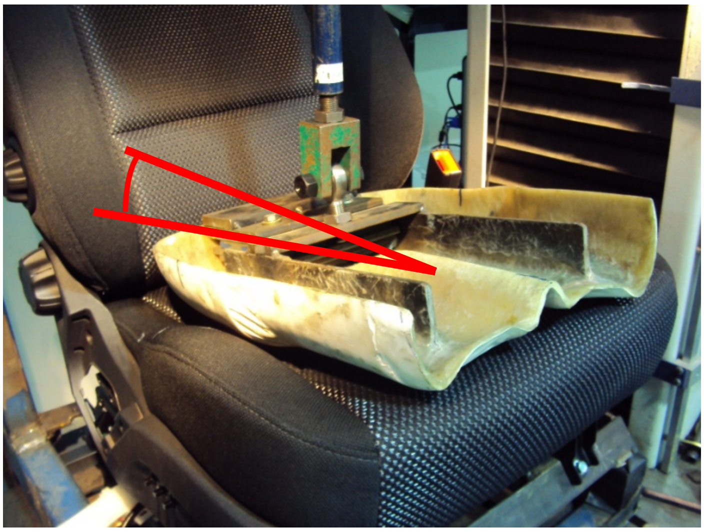

Figure 1: Positioning of an indenter form relative to seat at 10 deg. from horizontal

Representative Australian production level seats were used for testing. The seat was tested according to following positional rules:

- Seat track set at mid-travel
- Cushion height at mid-travel. Where possible adjusted from both front and rear

The environmental conditions were:

- Temperature 23° C (+/- 2°)

- Humidity 50% +/- 10%

Seats were pre-conditioned and tested in an un-deflected and undistorted state. H-point was determined according to produces outlined in SAE J826. Manikin legs were not applied. Force was zeroed at preload and the form impressed the seat cushion at constant velocity (5 mm/s) until a force of 950N was applied. The indenter was then fully retracted. Force was recorded between 0-950 N with a precision of 10^{-4} N, and deflection was recorded with a precision of 10^{-5} mm. All measurements were repeated and averaged.

Measurements were taken on a fully trimmed seat (Figure 1), on a seat with trim removed (foam on suspension) (Figure 2), on the seat suspension only (Figure 3), on the foam pad only (Figure 4) and on a foam pad with an intermediate neoprene layer, simulating a soft matter indentation (Figure 5). This latter measurement was also compared to an identical measurement on a non-contoured foam block of similar foam hardness.

Figure 2: Indentation on seat with trim removed

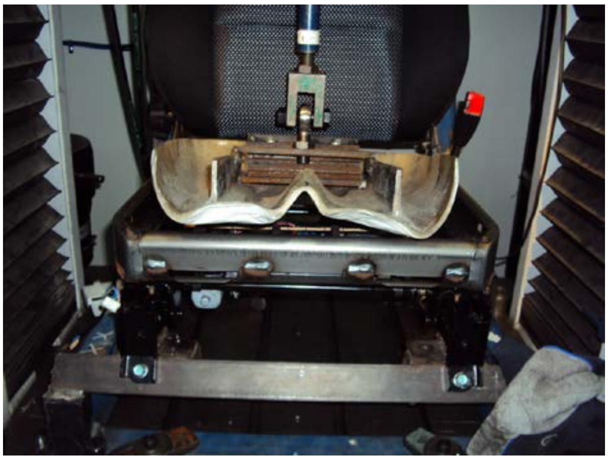

Figure 3: Indentation on seat suspension with foam and trim removed

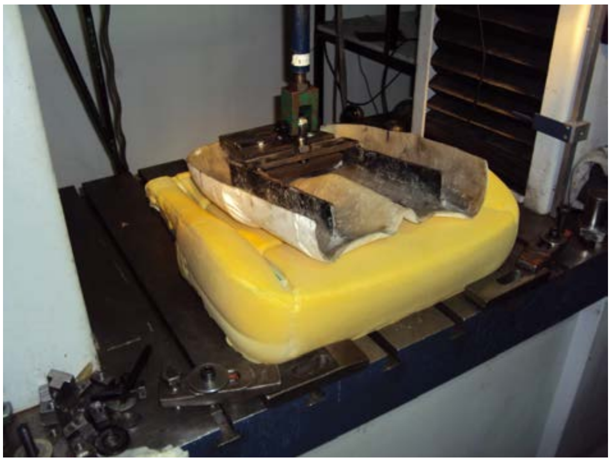

Figure 4: Indentation on foam pad only (no seat)

Figure 5: Indentation on foam pad with intermediate neoprene layer (no seat)

Human geometric model

The data used for modelling thigh and buttock geometry were taken on three subjects, using a whole-body three-dimensional scanner. The scanner used for this study was the Vitus Smart (Kaiserslautern, Germany) whole-body laser scanner. An individual scanned using the Vitus Smart scanner will on average yield 700,000 to 1 million voxels that correspond to the surface of the scanned body. The three thigh-buttock forms produced are representative of the following percentiles using internal data from an Australian anthropometric study:

- 5th percentile female
- 50th percentile male
- 95th percentile male

Height and weight were not the measurements used to classify subjects as a representation of these percentiles. The measurements used were ‘hip breadth’ (seated) and ‘buttock-to-knee length’. These measurements provide a better representation of the variation in buttock/thigh shapes that would be encountered in automotive drivers.
The database used to determine the percentiles represents the general population of a Western population (n=857; 432f/425m). No recent data accurately represent the general Australian population. The bivariate percentiles of the combined hip breadth (seated) and buttock-to-knee length distributions (Table 1) used in this study closely represent the selected Australian and the US population, assuming that Australia is now reaching the same levels of overweight and obesity as the US.

Table 1: Anthropometric measurements of three subjects, representing three bivariate percentiles.

Subject	Hip breadth (seated) (cm)	Buttock-to-knee length (cm)
5th percentile female	32.0	52.0
50th percentile male	34.5	60.4
95th percentile male	39.1	67.0

Each subject was scanned twice in three postures while wearing form fitting underwear. The subject was required to be in the following positions (Figure 6):

- Feet shoulder width apart with knees bent and the torso flexed at the hip to create a 90 degree angle between the torso and legs.

- Feet shoulder width apart with knees bent and the torso flexed at the hip to create a 110 degree angle between the torso and legs.
- Standing straight, feet shoulder width apart

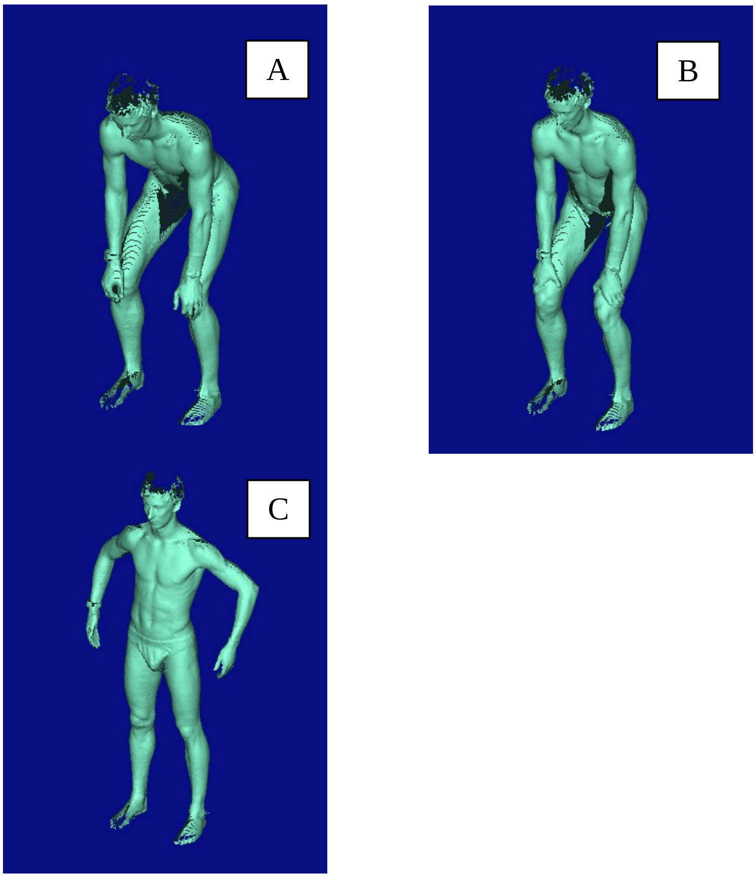

Figure 6: Example of 50th percentile male scanned with: (A) Feet shoulder width apart, knees bent and torso flexed at the hip for 90 degree angle between the torso and legs, (B) Feet shoulder width apart, knees bent and torso flexed at the hip for 110 degree angle between the torso and legs, (C) Standing straight, feet shoulder width apart

A resulting thigh-buttock-trunk surface shell for the 95th percentile subject in posture A is depicted in Figure 7. This model was also further on used for the analytic model and simulation.

Offsets were used to account for the compression of the skin, muscle and fat expected through sitting in a seat. A 6 mm layer of neoprene (Shahbeyk and Abvabi, 2009; Norpoor et al., 2008) was used to represent skin in the outer shell and various thicknesses of foam, modelling muscle and fat, are required to accurately represent the expected level of compression. Three foam thicknesses are representative of three different body corpulence percentiles. Based on literature and the analysis of magnetic resonance imaging scans (Al-Dirini et al., 2012), the following foam thicknesses were selected:

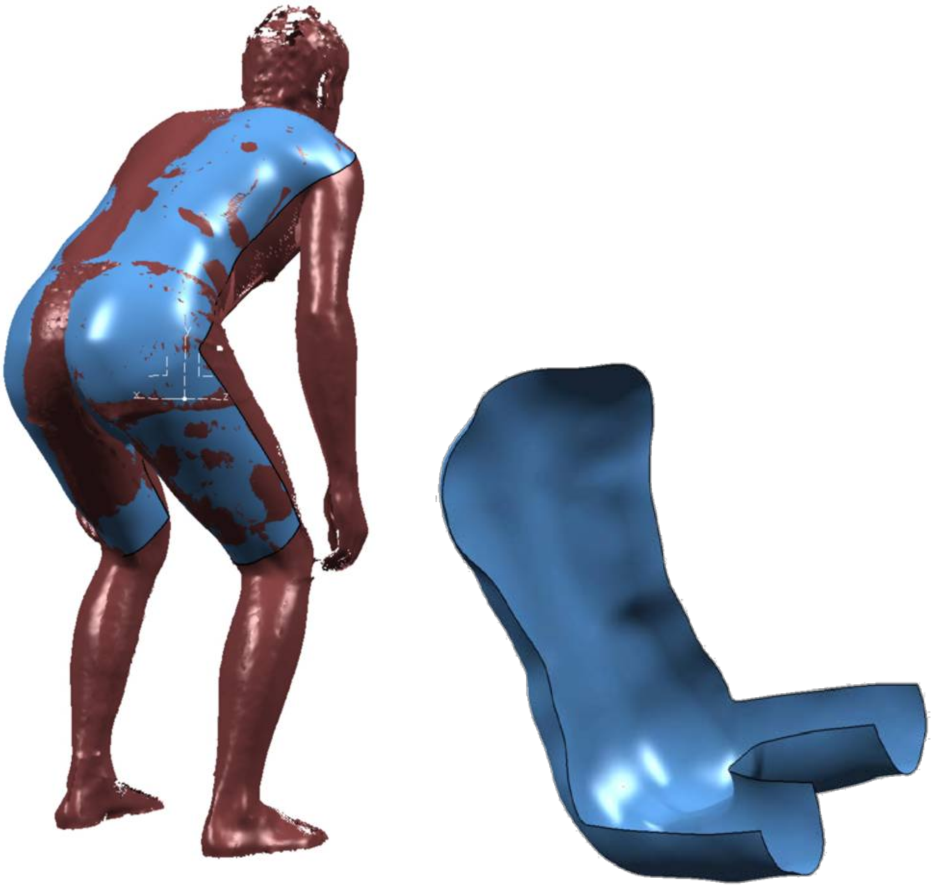

Figure 7: 3D scan resulting surface model for 95th percentile (Table 1), posture A

- 5th percentile (f) 0mm
- 50th percentile (m) 40mm
- 95th percentile (m) 65mm

Therefore, each thigh-buttock model is made of up three distinct layers; a hard shell, foam and neoprene (Figure 8). The hard shell is offset from the original scans by the thickness of the neoprene and foam. Down scaled models were designed off this generic model

- A two layer 6mm neoprene on hard shell structure. This model covers thin to moderate thigh and buttock proportions, but not the more fleshy upper percentiles. It is required for computational efficiency purposes during initial system optimization performed in this study.

- A hard shell structure. This model allows even more time efficient FEM simulation and comparison with physical indenter results.

Figure 8: Three layer thigh – buttock model for 95th percentile (Table 1), posture A

To replicate the effects of skin, a neoprene rubber layer was modelled as a hyperelastic material with viscoelastic behaviour. A Neo-Hookean material model was used to model this behaviour in FEM, and a uniaxial tensile strength test was conducted using an Instron testing machine to develop the neoprene rubber material model. Clamp motion was set to a speed of 5 mm/s. The hard shell assumption was used for a rigid indenter, which was modelled using the default structural steel linear elastic material model.

Seat model

All models were designed and modified in Solidworks® (Dassault Systemes, Paris), exported and meshed in ANSYS V13 WB (Canonsburg, USA), where finite element analysis was performed.

The analytical model is based on the CAD assembly of a Ford Territory seat supplied by Futuris, which was significantly modified for analysis. The assembly was reduced to include only parts of interest for frame, suspension and untrimmed foam pad, and a new assembly was created with properly defined connections. Due to the quasi-static nature of the analysis, the new assembly had all the nuts, bolts, washers and unnecessary components removed. Nevertheless the model was too large and failed to converge due to the high complexity in the geometry of the parts and the high level of non-linearity in the model (material and contact non-linearity). Even with a bonded contact assumption, the model was still too large and failed to converge. At this stage, the new assembly was reassessed, and the different parts were remodelled to a less complex geometric representation. In the remodelling stage, cosmetic curves were disregarded, bonded parts of the seat structure were combined as one part and bolsters and side supports of the seat cushion were smoothed out. The final assembly was successfully imported to ANSYS WB using the ANSYS toolbar in Solidworks®.
The seat cushion is made of open-cell PU foam. Open-cell PU foam is highly compressible due to its microstructure. Its structure has pours of air trapped inside it. When the PU foam cushion undergoes initial compression, the air inside the pours is pushed out. During this process, the foam only deforms in the direction of compression. Due to this behaviour, the Poison’s ratio is assumed to be zero in the foam material model. Furthermore, hyper-elasticity can be noted in the behaviour of foam under compression as it is able to undertake high strains without failing (Mills, 2007). Based on the above notes, a hyper-elastic Ogden second order material model with viscoelastic behaviour was used to model the PU seat cushion. As only quasi-static loading is investigated, seat structure material is assumed to be the default steel linear elastic material model in ANSYS WB v13. This was deemed acceptable as the structure and its components do not undergo any excessive loading that could drive it into failure.

3 Results

Suspension seat parameters

Tables 2 and 3 provide indentation-deflection results from the physical measurements on a suspension seat in the laboratory. The identical SAE AM50 type indenter was used for all measurements. Table 2 provides results for the different properties measured: the fully trimmed complete seat, the same seat with fabric and laminate removed, the same seat with fabric/laminate and seat foam pad removed, the seat foam pad only with a neoprene mat on top, the same seat foam pad without neoprene mat, an unformed foam block with a neoprene mat on top, and the same foam block without neoprene mat. Table 3 provides the relative deflection data in comparison of the different properties.

Table 2: Seat and foam indentation results for rigid indenter.

	Ref	Maximum Deflection [mm]	Maximum Force [N]
Fully trimmed seat cushion	A1	-41.1102	-952.129
Untrimmed seat cushion	A2	-42.9845	-953.719
Seat suspension only	A3	-24.8786	-981.409
Cushion pad + Neoprene fabric	B1	-32.8404	-953.255
Cushion pad only	B2	-33.0054	-953.226
Foam block + Neoprene	C1	-44.97	-950.449
Foam block	C2	-48.2931	-952.144

Table 3: Seat and foam indentation relative results for rigid indenter.

	Ref	Δ Maximum Deflection [%]
Contribution of production fabric to seat cushion	A1-A2	-5%
Contribution of suspension	A1-A3	61%
Contribution of neoprene on foam pad	B1-B2	-1%
Contribution of mould/contour	B1-C1	-27%
Contribution of neoprene on foam block	C1-C2	-7%

Table 4: Seat and foam stiffness calculated from experimental data (Table 2-3).

Material Ref	Young's modulus @ 196 N [N/mm]	Young's modulus @ 490 N [N/mm]
A1	17.68	19.92
A2	16.65	19.17
A3	14.61	24.64
B2	24.26	25.60
C2	15.80	9.69

Table 4 provides the calculated Young's modulus for all measured properties, with the exemption of the measurements including an intermediate neoprene layer, as those measurements were not relevant for stiffness calculation. Consistent with literature, 196 N and 490 N were chosen as reference points for calculating Young's modulus. Results were selected from the best trial out of two repeated measures and offset corrected.

Human and seat model

The optimized seat frame, suspension and foam pad CAD data were transformed and meshed into finite-element models and indented by a two layer, soft surface human finite-element model (Figure 9), as well as a hard shell, human finite-element model of equal geometry (Figure 10-11).

Table 5: Seat, foam model and indenter material properties for single layer model as reported by ANSYS.

Property	*Base for Cushion*	*Suspension*	*Cushion pad*	*Indenter*
Nodes	680	4035	30139	1227
Elements	537	3786	136289	1154
Material	Structural Steel	Structural Steel	CF45 foam	Structural Steel
Volume	1.1497e-003 m^3	2.3303e-004 m^3	1.9072e-002 m^3	2.5309e-003 m^3
Mass	9.0248 kg	1.8293 kg	19.072 kg	19.868 kg

Converging results with the least computational effort were achieved for a bonded connection between cushion and seat base as well as cushion and suspension, no separation between neoprene and indenter shell (Figure 9) and a frictional connection between cushion pad and neoprene.

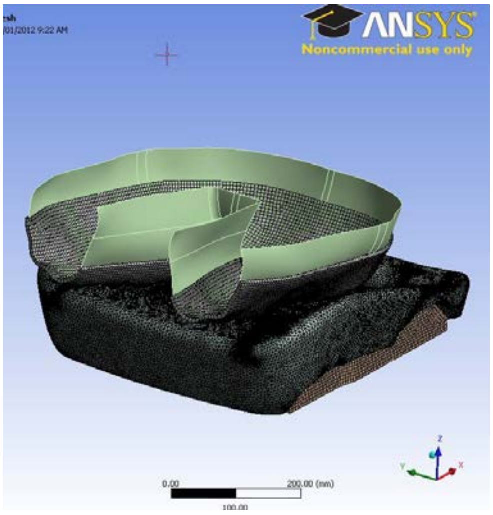

Figure 9: Two layer thigh – buttock final model for 95th percentile (Table 1), posture A

Four springs with longitudinal stiffness of 9 N/m @ 22 N and 38 N/m at 523 N were chosen for the suspension.

The masses for cushion pad and indenter are shown as reported by ANSYS (19.072 kg and 19.868 kg) (Table 5), although these are obviously incorrect. Given that all other parameters and the simulation results were physically sensible, it appears that the incorrect masses constitute rather an ANSYS reporting error, than an effective parametric error.

The simulation runs of indentation were terminated at an indentation force of 950 N.

In order to achieve a closer comparison of force-deflection simulation results from the FE model with experimental measurements, the modified single layer FE model (Figure 10), based on thin 95th percentile anthropometry was then used to represent a rigid (hard shell) indenter.

However it should be noted that proportions of physical and analytical indenters were not identical. Maximum deformation for both the single and two layer, soft surface indenter trials was 49mm, and Young's modulus for the suspension was 3.35 MPa. Optimized foam parameters for the simulation were

- density (reported by ANSYS) 1000 kg/m^3 and
- Young's modulus 0.76 MPa.

As a qualitative control measure, seat cushion contact surface (Figure 10) and seat cushion contact pressure (Figure 11) were recorded.

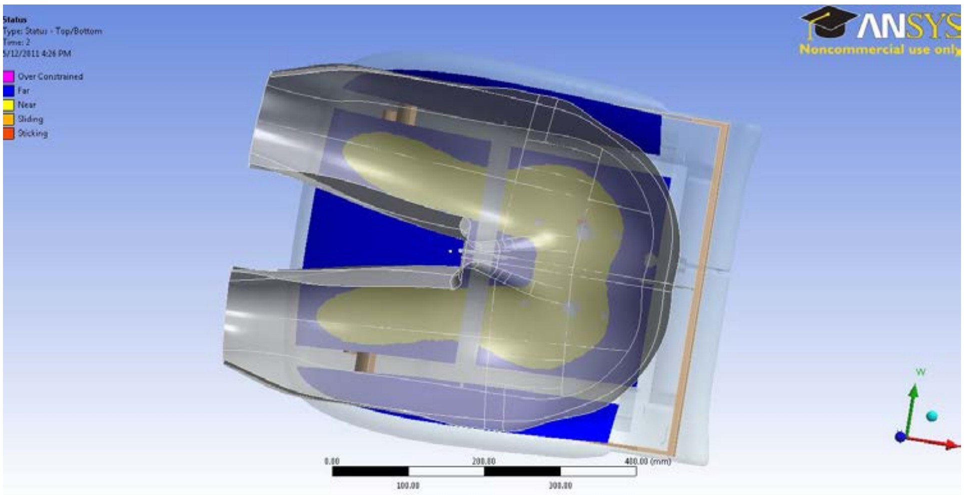

Figure 10: Single layer model simulated indentation on seat cushion: contact surface

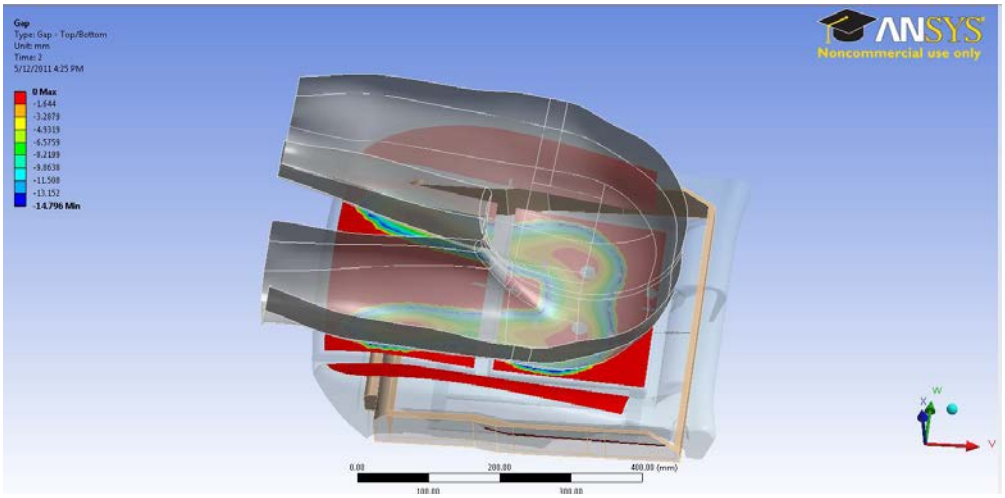

Figure 11: Single layer model simulated indentation on seat cushion: contact pressure

4 Discussion

Maximum seat cushion deflection for a fully trimmed (untrimmed) suspended seat under 950N load was found to be 41mm (43mm) under experimental conditions. Seat trim, i.e. production fabric was found to have very little influence on deflection, which was reduced by 5%.

On the other hand, seat suspension contributed 61% of total seat cushion deflection, which allows the conclusion that by optimizing a seat suspension system, thinner foam pads could be used under package critical conditions. Contour or mould of the cushion pad contributed to reduced foam deflection by up to 27%, compared to a non contoured or molded foam block with similar ILD hardness and foam density. The application of neoprene for simulating indentation with a soft tissue indenter (i.e. human thigh-buttock), contributed only a negligible 1% when used in combination with the cushion pad, and 7% less deflection when used with the foam block. The study should be repeated to compare the effects of other trim type, e.g. leather vs. fabric.

The measured foam stiffness of 24 N/mm @ 196 N compares well with the data provided by Murata et al. (2002) for their high performance foam (static spring constant of 7.5 N/mm @ 196N) and the results reported by Ebe and Griffin (2000 [2]) for optimum subjective comfort (stiffness of 16.6 N/mm). Conditions applied by Yamazaki (1992) for a soft cushion pad (13.6 N/mm spring constant) and a standard cushion pad (15.3 N/mm spring constant) equally support those data. The results also coincide with reports of high energy dissipation foam pads used in Japan, if compared to other countries (Mills, 2007).

Maximum force-deflection of the untrimmed suspended seat (43mm) was approximated within 12% error margin in a finite-element model (49mm deflection) with satisfactory precision, particularly as the physical and the virtual indenter shells were not identical in shape (50^{th} univariate percentile of US population vs. 95^{th} bivariate percentile of combined population US/AUS).

The foam and shell density reported by ANSYS is incorrect, by a factor of 20 for PU foam when compared to physical evidence. Consequently foam and shell mass reported by ANSYS was also significantly overweighed (19.07 kg for the foam pad and 19.87 kg for the shell), again reflecting the factor 20 for foam. This oddity was also found in the data reported by Mergl et al. (2004) and will need to be further investigated.

In a qualitative assessment, pressure distribution simulated in the hard shell indentation model is very similar to pressure distribution measured on an equivalent physical property for a suspended seat. The seat pressure distribution and seat indentation simulation model “BOB” (body objective biometrics) is therefore suitable for seat comfort optimization.

Opportunities for improvement

Current geometric CAD seat models need simplifying to ensure the FEM works and generates only a small simulation error. There is opportunity for optimising within current FEM capabilities and, in the future as the processing power increases, will enable greater accuracy for simulation.

Seat cushion thickness reduction is a primary focus of package efficient seat design. As seat cushion spring suspension contributes 61%, and seat cushion contour contributes 27% of deflection on a 50 mm thick cushion, there is an opportunity to reduce overall thickness of the seat cushion (~50mm) while maintaining comfort by further developing cushion pad contour and the cushion spring suspension system.

The modelling technique’s key performance characteristics scalability (e.g. dimensional variation of seat cushion and/or indenter), adjustability (e.g. softer foam, softer indenter, stiffer springs), portability (e.g. the model can be replicated in other FEM simulation packages) and extension (e.g. addition of parts like heater mats, cooling systems, spacer mats etc.) provide opportunity for a wider range of application.

Significant engineering time/cost savings will depend on the quality level of initial CAD seat design, and processing power compared to typical lengthy empirical testing. A PC cluster based simulation, running without operator input, will take about 2 hours.

5 Conclusions

The study modelled and simulated human-seat interface pressure at a reliable level required for comfort predictions, and provide insight into the contribution of suspended seat structures to the force-deflection behaviour of the combined human-seat system, which is important for both vibration comfort and static comfort analysis. By simulating a FORD physical test on a production seat, which is representative of human-seat interaction, an approximation was achieved within reasonable error. Thus the contributions of seat components to seat force-deflection behaviour were established, leading to the determination of model parameters for human-seat interface simulations. Future work will have to expand on the outcome, with an emphasis on developing a full range of human shell models, and simulating their impact on seat force deflection behaviour. Moreover, a quantitative validation of simulation results versus physical pressure maps remains to be undertaken.

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