Applied Ergonomics 56 (2016) 127–135

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Constitutive kinematic modes and shapes during vehicle ingress/egress

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A R T I C L E I N F O

Article history:
Received 2 November 2015
Received in revised form
28 February 2016
Accepted 29 March 2016

Keywords:
Ingress/egress
Principal component analysis
Comfort
Motion analysis
Older users
Vehicles
Cars
Ergonomics

A B S T R A C T

A study was undertaken to investigate the kinematics of older users of passenger vehicles during ingress/egress and to seek correlations between their movement and comfort rating assigned by the subjects to the ease of vehicle ingress and egress. A principal component analysis was performed on the subjects' kinematics to identify the underlying modes of movement employed by the subjects. It was found that a small number of modes could describe the movements of all the subjects across all of the vehicles. Within the subspace defined by the modal vectors, shapes were found which correlated to the comfort rating for ease of ingress and egress which the subjects had assigned to each of the cars. Knowledge of these shapes which correspond to good and poor ingress and egress will be useful to the designers of interiors and exteriors of passenger vehicles for the older person. It is recommended that vehicle designs for the older person should attempt to avoid body positions which require excessive ankle articulation and lumbar flexion/extension during ingress and egress.

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1. Introduction

Comfort is a subjective concept which is difficult to objectively define and measure as there is no universally accepted operational definition of comfort (Leuder, 1983). Many researchers have adopted the definition of comfort as being "the absence of discomfort" (Hertzberg, 1972) as it is more straightforward to quantify discomfort than to measure comfort. Comfort and discomfort can best be understood under a theory of complexity since it emerges from a chain of interaction processes between the human and several elements of a system (Da Silva et al., 2012). The perception of comfort and discomfort is a multifactorial sensation which is a function of numerous factors mutually interacting and interacting with the subject in a complex manner.

In recent years, car manufacturers have increased their interest in vehicle comfort in general and ease of ingress/egress (I/E) in particular. To study ease of use, automobile manufacturers have sought validation using physical mock-ups of vehicles and subjective judgements given by subjects to correlate with vehicle dimensions (Tessier, 2000).

However with a growing ageing population and an increased number of people maintaining an active lifestyle well into their 80s, it is suggested that the design of vehicles would benefit from a clear understanding of the limitations related to age-associated reductions in physical mobility (Berman et al., 1988). According to Smith and Sethi (1975), joint flexibility declines by approximately 25% in older adults. These age-related restrictions occur naturally within an ageing musculoskeletal system, for example joint range of motion decreases with age and reduction in joint flexibility can lead to less efficient movement patterns (Daley and Spinks, 2000; Vandervoort, 2002).

Sarcopenia also occurs with the ageing process and specifically refers to loss of skeletal muscle mass. All men and women experience some degree of sarcopenia (defined as losses greater than 2 SD below the mean for young healthy controls) (Doherty, 2003); with prevalence ranging from 13 to 24% in persons aged 65–70 years; and over 50% for those older than 80 years (Baumgartner et al., 1998).

Rising from any chair is a biomechanically demanding task for the older person which requires co-ordination, balance, adequate mobility and strength (Riley et al 1991, 1997; Ikeda et al., 1991). Research suggests a range of biomechanical factors affect the ability

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http://dx.doi.org/10.1016/j.apergo.2016.03.017
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to rise from a seat such as knee torque, horizontal and vertical linear momentum, balance, choice of seat rise strategy and upper and lower extremity strength (Hughes et al., 1994; Janssen et al., 2002) and older adults have been found to increase hip flexion and optimise knee joint velocities whilst rising from a chair (Schenkman et al., 1990; Hughes and Schenkman, 1996).

These difficulties are exacerbated during ingress/egress of a vehicle for an older person (Robert et al., 2014). A complete description of the joint loads occurring during I/E motions is not currently available (Robert et al., 2014). Few studies have reported on the I/E movement (Menceur et al., 2008) although existing studies of I/E movement have focussed on healthy able-bodied people (Giacomin and Quattrocolo, 1997; Lestrelin and Trasbot, 2005; Lempereur et al., 2005).

However, vehicle accessibility and meeting physical limitations related to age is a key vehicle selection criterion for the older driver (Zhan et al., 2013) and therefore fulfilling the requirement of ease of use during ingress/egress of vehicles is of commercial, as well as social, importance. It was therefore considered necessary to analyse the movement during I/E of vehicles by the older person and to consider the influence on I/E ease of use comfort levels of movement patterns adopted by the older person.

2. Materials and methods

The movement of 30 subjects (17 female, 13 male) during ingress and egress into 4 vehicles was measured. The age range of the subjects was 55–69 years with a mean age of 62 years and standard deviation of 4.2 years. The weight range of the subjects was 61 kg–120 kg with a mean weight of 79 kg and standard deviation of 18.2 kg. The height range was 1.52 m–1.93 m with a mean of 1.63 m and standard deviation of 0.073 m.

The ingress, seated posture and egress of the subjects was measured using the magneto-inertial Xsens MVN Awinda system consisting of 17 wireless motion tracking sensors. Each sensor contains 3 orthogonal linear accelerometers and 3 orthogonal gyroscopes. Angular drift about horizontal axes was eliminated by sensing the Earth's gravity and angular drift about the vertical axis was eliminated by using a magnotometer to sense the direction of the Earth's magnetic field.

Translational drift is more difficult to eliminate using an inertial measurement based system as there is, generally, no external reference. By default, the Xsens assumes a non-slip foot condition for the lower foot to remove drift in the horizontal plane and the Awinda sensors incorporate a barometer in each unit which can supposedly detect changes in altitude. The non-slip foot condition of the lower foot is not always valid, indeed the current study contains a situation when this assumption is violated, ie when the subject is seated in the vehicle and the feet are being lifted into the vehicle and the accuracy and repeatability of the altitude measurements are unknown. However for this study the absolute location, or even translational movements are not of significance but only the joint articulations and hence translational drift will not affect the results nor conclusions.

Xsens's MVN Studio software was used for the data capture. During the trial, the sensors attached to subjects were sampled at 60 Hz via a wireless interface and data stored on an i7 laptop personal computer.

A subject wearing the MVN Awinda system is shown in Fig. 1. The sensors are the small matchbox-sized boxes attached around the body. The sensors were attached to the subjects at the location listed in Table 1.

The vehicles used for the trials were large family cars (British market segment)/mid-size car (American market segment). Prior to the ingress/egress trials the subjects were instructed to adjust the seat and steering wheel positions to suit their driving style. The subjects were then instructed to open the vehicles driver's door, enter the vehicle at their own pace and sit in the driver's seat. When the subject had been seated in the driver's seat for approximately 3 s they were instructed to egress the vehicle which necessitated opening the driver's door and to close the door after their egression. The subject then moved to the next vehicle and continued until all 4 vehicles had been ingressed and egressed. The order in which the subjects encountered the vehicles was the same for all subjects; this was determined by the placement of the vehicles within the laboratory.

Between ingressing and egressing each vehicle, the sensors were re-calibrated to remove drift and motion artefacts resulting from any slippage of the sensors across the body. If there were any large movements of the sensors across the subjects' body during the trials, for example due to an impact contact with the vehicle structure, the sensors were repositioned before calibration and the trial repeated.

Immediately following the biomechanical trials, all of the subjects were asked to rate the ease of ingress and egress of each vehicle. The subjects were asked to assess the ease of ingress/egress based on an anatomical basis (eg individual joint articulation) and temporally (eg the moment of maximum comfort/discomfort during the ingress/egress event) but this was found to be confusing for the subjects and difficult to quantify. Therefore the subjects were asked to assess the ease of ingress/egress throughout the action on a scale of 1 (poor performance) to 5 (good performance).

It was assumed that the movement of the subjects could be represented by the linear superposition of a number of fundamental "modes" of motion where the number of modes is significantly less than the total number of degrees of freedom of the subject.

As an example of the concept of decomposing movements into fundamental modes, consider walking gait. Walking gait could be considered to be anti-phase swinging of straight legs. The motion does constitute a large component of the walking action but neglects many of the subtleties of gait and would be very impractical. Next introduce another movement which consists of some knee flexion with ankle dorsiflexion. The combined action of leg swing and knee/ankle shape would enable foot clearance from the ground during swing phase which would improve the gait relative to simple leg swinging but would still lack the finesse of real human gait. Therefore add more and more patterns of joint articulations until a motion indistinguishable from true gait is achieved. These patterns are the fundamental modes of gait. It is important to note that each of these modes typically contain articulations of numerous joints, all moving in phase.

This paper considers applying this deconstructive approach to analyse ingress/egress of vehicles and the task of identifying comfort rating versus movement correlation. This was undertaken by the identification of the appropriate linear combination of the modes of motion associated with vehicle ingress/egress which maximises their correlation to comfort assessments provided by the trials' subjects.

2.1. Theory/calculation

It will be assumed that the movement of the human body can be represented as a multi-rigid-body mechanism with $6 + 3^*N$ physical degrees of freedom where N is the number of joints each possessing 3 degrees of freedom. However rotation of some of these degrees of freedom may be restricted to virtually zero due to local anatomy. For example, the elbow can be modelled, for most applications, as a revolute hinge joint which releases the flexion/extension degree of freedom and the movement of the internal/

Fig. 1. Magneto-inertial motion capture system attached to a subject – the sensors are the small "matchboxes" attached to the subject.

Table 1
Location of sensors placed on the body.

	Head	
Left shoulder	Sternum	Right shoulder
Left upper arm		Right upper arm
Left fore arm		Right fore arm
Left hand		Right hand
	Pelvis	
Left upper leg		Right upper leg
Left lower leg		Right lower leg
Left foot		Right foot

external rotation and varus/valgus degrees of freedom being constrained to zero articulation. Six degrees of freedom are associated with the translations and rotations associated with the root segment, which was the pelvis for the current study. However human anatomy and physiology implies that these physical degrees of freedom do not operate independently, for example during gait hip, knee and ankle articulations follow a repeatable functional relationship. This relationship can be expressed as a constraint equation between the physical degrees of freedom. If the movement pattern has C constraint equations, the total number of degrees of freedom reduces to 6 + 3*N −C.

All of the physical degrees of freedom can be removed from the motion of a mechanism by the introduction of generalised degrees of freedom and constraint equations which relate the displacements of the physical degrees of freedom to the generalised degrees of freedom. The constraint equations take the form of a modal matrix where the columns of the matrix describe the shapes of the modes in terms of the physical degrees of freedom.

$$\mathbf{u} = \Psi.\zeta$$

where $\mathbf{u}$ is the vector of physical degrees of freedom (eg joint articulations)ψ is a matrix of constraint equations – the modal matrix.ζ is a vector of modal contributions of the generalised degrees of freedom associated with the shapes defined in the modal matrix.

The significance of the ψ modal matrix is that each column describes a mode, which is uncorrelated and orthogonal to all other modes; it is a constituent shape of the physical motion. If the length of the ζ vector is significantly less than the length of the $\mathbf{u}$ vector, the motion of the mechanism, or person, can be described in a more concise manner using a modal representation.

If the mechanism's position changes with time the above relationship becomes:

$$\mathbf{u(t)} = \Psi.\zeta(\mathrm{t})$$

where it is assumed that the modal matrix is time invariant. The columns of the matrix u(t) represent the displacement of the physical degrees of freedom at subsequent times and the columns of the matrix ζ(t) represent the contributions of the modal degrees of freedom at subsequent times.

The task in formulating ψ is then to identify an orthogonal set of modal vectors which retains a total variance in the data in excess of a predefined threshold. Principal component analysis (Hubert et al., 2005) was used for the calculation of the modal matrix ψ as implemented in MATLAB (Mathworks Inc, Natick, MA) eliminating modal components that contribute less than 2% to the total variation in the data set.

u(t), is available from physical measurement using the motion capture system and hence the modal contributions, ζ(t), can be calculated from:

$$\Psi^{\mathrm{T}}\cdot\mathbf{u(t)} = \Psi^{\mathrm{T}}\cdot\Psi\cdot\zeta(\mathrm{t})$$

As ψ is an orthogonal matrix this reduces to:

$$\Psi^{\mathrm{T}}\cdot\mathbf{u(t)} = \zeta(\mathrm{t})$$

from which the modal contributions can be calculated as the matrix u(t) is available from the motion captured data.

The modal matrix, ψ, defines an orthogonal base of a sub-space within the space traversed by the physical degrees of freedom whilst retaining 98% of the variance of the observed motion. Therefore operating within this reduced dimensionality can offer considerable computational advantages.

Modes are mathematical abstractions of the principal component analysis with no reference; the modes are the building blocks which can be assembled to create the posture of the subject. However the modes define a compact basis for representing the observed postures. Nor do modes correspond to the comfort ratings provided by the subjects, however it may be possible to construct shapes from a linear superposition of these modes which do possess a significant correlation to comfort ratings.

To this end shapes were constructed, defined in the orthogonal base of the modal matrix, which displayed maximal correlation to the vehicles' comfort ratings.

Let S = ϕ.ψwhere S is the shape matrix whose columns represent shapes which maximise the correlation of the shape contribution vector to the comfort rating. S is not necessarily an orthogonal matrix

ϕ is the shape contribution matrix defining the superposition of the modes within the shape matrix. ϕ is not necessarily an orthogonal matrix

The contributions of these shapes to the observed movement can be calculated from:

$$\theta(t) = S^T \cdot \mathbf{u}(\mathbf{t}) \quad (1)$$

where $\mathbf{\theta(t)}$ is the contributions of the shapes to the observed motions.

Because of the dimensional reduction of the modal degrees of freedom substitution, the sub-volume can be efficiently searched to identify the shapes which maximises the correlation and the ease of comfort ratings for I/E assessed by the subjects.

Spearman rank correlation coefficients (Lehman, 2005) were calculated between the shapes and the ease of comfort ratings used as this procedure can compare the discrete, qualitative assessment of the comfort rating questionnaire against the continuous, quantitative measurement of biomechanical variables.

To calculate the shapes which maximise the magnitude of the correlation coefficients, the following procedure was iteratively applied:

Step 1: Calculate the shape contribution to the observed time history of physical degrees of freedom from equation (1) assuming the shapes are equal to the modes.
Step 2: Calculate the Spearman rank correlation coefficients between the maximum change in amplitudes of the shape contributions and the ease of I/E comfort ratings as assessed by all of the subjects to all of the vehicles.

For each shape

Step3: Perturbate the shape by sequentially adding one of the modes multiplied by a scaling factor.
Step 4: Calculate the magnitude of the Spearman rank correlation coefficients between the maximum change in amplitude of this perturbated shape's contribution and the I/E comfort rating.
Step 5: If the correlation decreased as a result of the perturbation:

disregard this perturbation.
Else if the correlation increased as a result of the perturbation: update the shape to include this perturbation.

Step 6: Repeat from step 3 for all of the modes.
Step 7: Decrement the scaling factor and repeat from step 3 unless the change in the magnitude of the correlation coefficient is less than a pre-defined threshold.
Step 8: Repeat for all shapes.

3. Results

Intra-segmental rotations were recorded using the magneto-inertial motion tracking system for all subjects and all vehicles — 120 trials. The ingress and egress sections of the movement were identified by observation of the motion data. Twenty-six of the subjects were observed to employ the “Left (lateral) leg first” strategy and four used the “two legs out” strategy (Chateauroux and Wang, 2010).

For the subjects employing a left-leg-first strategy, ingress was considered to start when the subject adopted a single leg stance and finished when both heels contacted the floor of the vehicle. The egress commenced when one foot departed the vehicle floor and finished when a two foot stance on the external floor was adopted.

For the subjects employing a two-legs-out strategy, the ingress was considered to start when knee flexion exceeded 15° and finished when both heels contacted the floor of the vehicle. The egress commenced when one foot departed the vehicle floor and finished when a two foot stance on the external floor was adopted.

Time histories of the following 42 physical degrees of freedom were sampled at 60 frames per second:

Neck Joint

Lateral Bending Right/Lateral Bending Left; Axial Rotation; Flexion/Extension

Right/Left Shoulder

Abduction/Adduction; Internal/External Rotation; Flexion/Extension

Right/Left Elbow

Ulnar Deviation/Radial Deviation; Pronation/Supination; Flexion/Extension

Right/Left Wrist

Ulnar Deviation/Radial Deviation; Pronation/Supination; Flexion/Extension

Lumbar Joint

Lateral Bending Right/Lateral Bending Left; Axial Rotation; Flexion/Extension

Right/Left Hip

Abduction/Adduction; Internal/External Rotation; Flexion/Extension

Right/Left Knee

Abduction/Adduction; Internal/External Rotation; Flexion/Extension

Right/Left Ankle

Abduction/Adduction; Internal/External Rotation; Dorsiflexion/Plantarflexion

The musculoskeletal analysis package BoB (Biomechanics of Bodies) (Shippen and May 2012) was used to undertake the principal component analysis (PCA) of the time histories of physical degrees of freedom. The PCA returns the constituent modes of the time histories and the modal contributions throughout the time history therefore whilst the differing lengths of the trials affect the modal contribution histories it does not affect the modes. The PCA transform retained 98% of the variance in the original data set which resulted in a dimension reduction to 18 orthogonal principal component vectors. The modes which were calculated by the PCA are shown in Fig. 2. The relative joint articulations are of significance within the mode and not the absolute magnitude of any joint angle hence in Fig. 2 the mode is illustrated with the maximum joint articulation set to 60° and tablulated in Table 2.

These modes are similar in form to the results of a Fourier analysis of a waveform. Any waveform can be decomposed into the linear superposition of an orthogonal base defined by harmonic sine waves; in this analogy, the modes calculated by the PCA correspond to the harmonic sine waves.

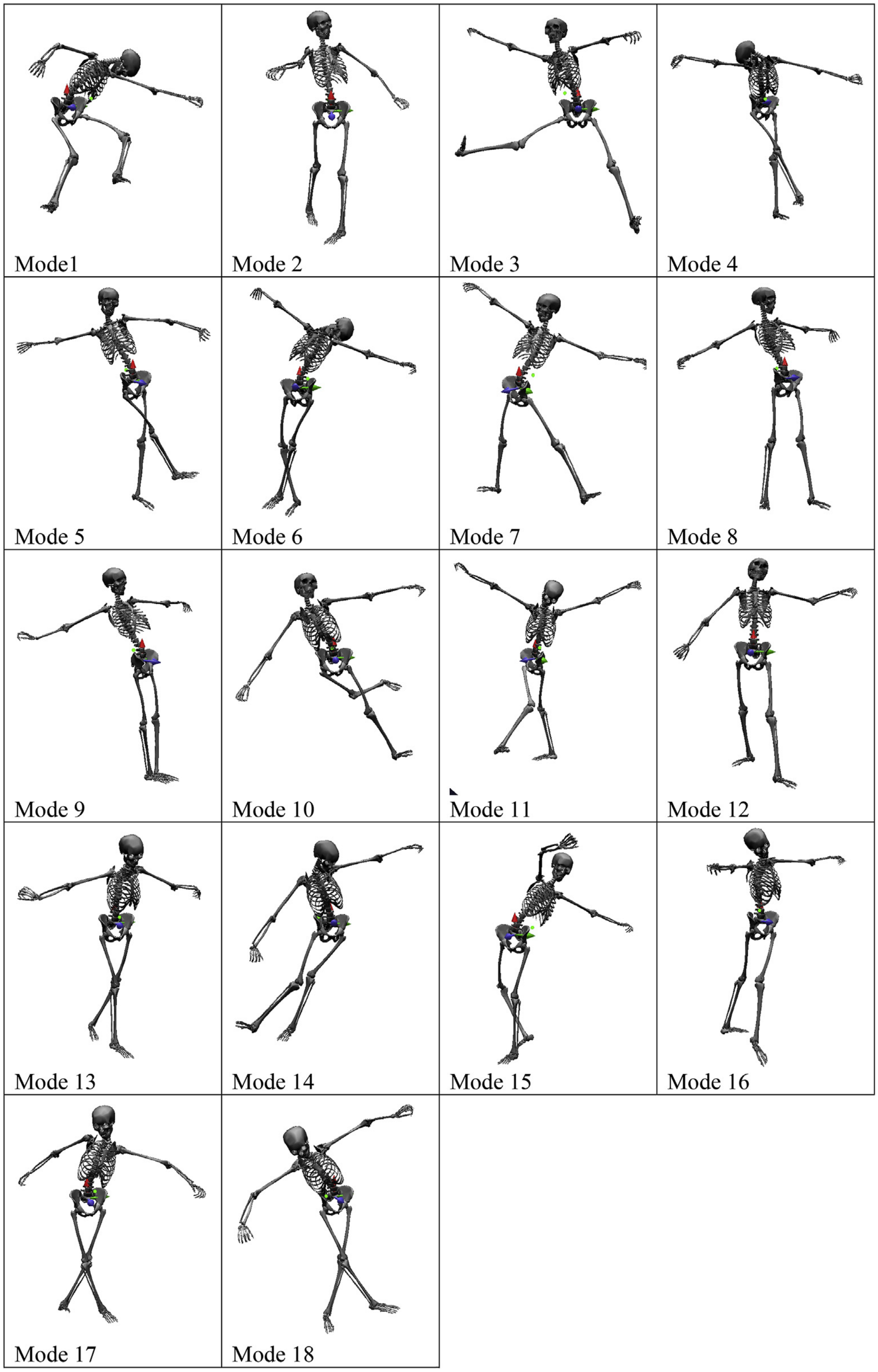

Fig. 2. The mode shapes forming an orthogonal base.

Within the orthogonal base defined by these modes, the subspace was searched to create shapes as a linear combination of the modes which maximise the correlation between these shapes in the observed movements and the comfort ratings as described in the Theory/Calculation section.

Fig. 3 shows the Spearman rank correlation coefficient (Sockloff and Edney, 1972) between each of the shapes and the comfort ratings ordered into decreasing correlation coefficient. Also shown on Fig. 3 are the correlation coefficients corresponding to a significance level for the null hypothesis of 5% and 1% for a sample size N = 120 (30 subjects, 4 vehicles). The shapes which maximise the comfort rating correlations are shown in Fig. 4. Shape 1 has the

Table 2
Descriptions of the ingress/egress constitutive shapes. Angles in shapes normalised to 60°.

Shape	Movement 1	Movement 2	Movement 3	Movement 4	Movement 5
1	Lat wrist	Lat elbow	Med shoulder	Lat shoulder	Med wrist
r = 0.141	Flex/Extension	Pro/Supination	Ab/Adduction	Ab/Adduction	Flex/Extension
Degrees	60	52.769	52.6915	46.6106	45.0156
2	Lat wrist	Lat knee	Lat shoulder	Lumbar	Med shoulder
r = 0.062	Pro/Supination	Rotation	Rotation	Flex/Extension	Rotation
Degrees	60	52.5741	48.2938	45.5633	36.8745
3	Med knee	Lat wrist	Med hip	Med wrist	Lumbar
r = −0.131	Rotation	Pro/Supination	Flex/Extension	Pro/Supination	Rotation
Degrees	60	59.0037	54.6266	50.0164	43.817
4	Lat elbow	Med hip	Med elbow	Med knee	Lat elbow
r = −0.166	Flex/Extension	Ab/Adduction	Flex/Extension	Ab/Adduction	Pro/Supination
Degrees	60	50.2631	49.624	42.1757	38.2652
5	Lat elbow	Med elbow	Med hip	Med knee	Lat elbow
r = −0.168	Flex/Extension	Flex/Extension	Ab/Adduction	Ab/Adduction	Pro/Supination
Degrees	60	53.6643	33.457	31.5703	30.4298
6	Lat knee	Med knee	Lat elbow	Lat ankle	Med wrist
r = −0.195	Flex/Extension	Flex/Extension	Flex/Extension	Dorsi/Planta	Pro/Supination
Degrees	60	42.9608	41.6152	37.7741	37.4061
7	Med ankle	Lumbar	Med ankle	Med knee	Lat ankle
r = −0.201	Rotation	Flex/Extension	Dorsi/Planta	Rotation	Dorsi/Planta
Degrees	60	48.2779	47.7243	44.8343	41.285
8	Med shoulder	Lat wrist	Lat hip	Lat ankle	Lat shoulder
r = −0.206	Ab/Adduction	Flex/Extension	Flex/Extension	Ab/Adduction	Rotation
Degrees	60	50.0767	49.1145	40.45	38.1979
9	Lat elbow	Med ankle	Med shoulder	Med shoulder	Lat elbow
r = −0.210	Ulnar/Radial	Rotation	Flex/Extension	Rotation	Pro/Supination
Degrees	60	52.5541	48.8741	42.2428	34.5871
10	Lat wrist	Med ankle	Med wrist	Neck	Med shoulder
r = −0.211	Flex/Extension	Rotation	Flex/Extension	Flex/Extension	Rotation
Degrees	60	46.5376	32.0503	30.4351	30.1119
11	Lat elbow	Lat elbow	Lumbar	Med ankle	Med shoulder
r = −0.220	Ulnar/Radial	Pro/Supination	Flex/Extension	Rotation	Flex/Extension
Degrees	60	59.2692	50.0241	46.9415	38.7324
12	Med ankle	Lat elbow	Lat ankle	Med knee	Neck
r = −0.224	Rotation	Ulnar/Radial	Dorsi/Planta	Flex/Extension	Lateral Bending
Degrees	60	58.8646	49.8953	48.5324	36.9639
13	Med ankle	Med knee	Med hip	Med knee	Lat elbow
r = −0.242	Rotation	Rotation	Rotation	Flex/Extension	Pro/Supination
Degrees	60	53.3202	47.8583	33.4751	23.9173
14	Med wrist	Med knee	Lumbar	Lat elbow	Med ankle
r = −0.243	Pro/Supination	Flex/Extension	Flex/Extension	Pro/Supination	Rotation
Degrees	60	44.9753	40.9082	39.4216	36.3352
15	Med ankle	Lumbar	Lat ankle	Lat elbow	Med knee
r = −0.249	Rotation	Flex/Extension	Dorsi/Planta	Pro/Supination	Rotation
Degrees	60	48.4638	39.2183	38.1486	33.7687
16	Med ankle	Med ankle	Lat ankle	Med ankle	Lumbar
r = −0.258	Rotation	Dorsi/Planta	Dorsi/Planta	Ab/Adduction	Flex/Extension
Degrees	60	50.9939	41.2251	37.5436	35.0978
17	Med ankle	Med ankle	Lat ankle	Lumbar	Med ankle
r = −0.269	Rotation	Dorsi/Planta	Dorsi/Planta	Flex/Extension	Ab/Adduction
Degrees	60	45.5897	43.8549	42.4098	35.3605
18	Med ankle	Med ankle	Med knee	Lumbar	Lat ankle
r = −0.270	Rotation	Dorsi/Planta	Rotation	Flex/Extension	Dorsi/Planta
Degrees	60	41.0316	40.895	38.2871	37.0919

maximum Spearman rank correlation coefficient of 0.141, shape 2 has the next largest correlation of 0.0620 through to shape 18 which has a correlation coefficient of −0.27.

Each of these shapes are described as the relative articulations of each of the joints – the absolute size of the articulations of each of the joints within the shape has no meaning as it is only when these shapes are combined to recreate the observed motion that the magnitude of the shape has a physical significance. Table 1 lists the 5 largest relative joint articulations in each of these shapes. Medial (Med) refers to the joint closest to the centreline of the vehicle and lateral (Lat) refers to the joint furthest from the vehicle's centreline.

4. Discussion

The magneto-inertial motion capture system used was found to be suitable for the task of measuring the movement of the subjects during the ingress/egress activity. The sensors which were used for the trials introduced little inconvenience to the subjects and were rapidly attached to the subjects' bodies. There was an occasional collision between the sensors and the vehicle but the real-time monitoring of the data made identification of these events easy to see and the trial was immediately repeated. The collected data was clean and did not require further processing. Translational drift was observed, particularly in the vertical direction, but this was not significant to the study as joint articulation was of primary interest.

The study commenced by researching the correlation between individual joint angles and comfort ratings but poor correlation coefficients were found across the body and no correlation coefficient was found in excess of a significance level of 5%. This suggested to the researchers that comfort during ingress/egress was

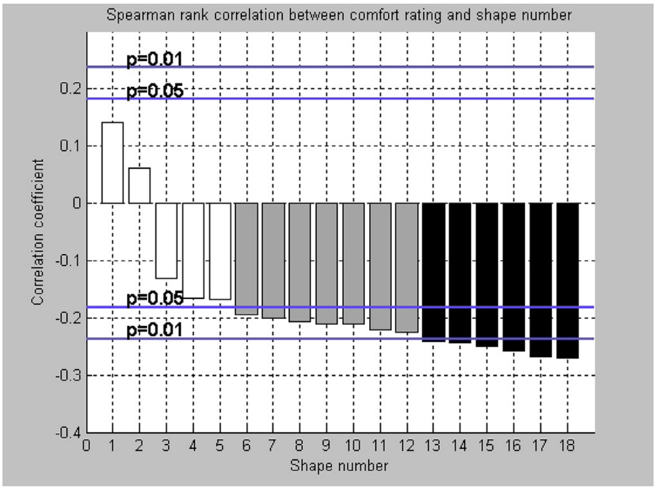

Fig. 3. Correlation between comfort rating and optimised shapes.

being assessed by the subjects as a multi-joint phenomenon rather than on an individual joint basis.

A principle component analysis of the joint articulations during ingress and egress indicate that a sub-space with a dimensionality of 18 contained 98% of the variance of the joint articulations.

The lower the dimensionality of the movement, the more simplistic is the motion which is observed (Bronner and Shippen, 2015). By way of an example, consider the gait example described above; if gait were to be described as anti-phase leg swinging it would have a dimensionality of 1, include the knee flexion/ankle dorsiflexion and the dimensionality increases to 2, a recognisably human gait would have a dimensionality of about 10. The existence of the model sub-space does not imply that the subject will exhibit any of these modes during the trial, but that the observed motion is a linear superposition of these underlying modes. The modal sub-space also demonstrates that the joint movements were not operating independently but rather as a combination of fundamental shapes. These modes can be described by the relative size of the joint articulation occurring within the modes and the original motion can be expressed, in a concise manner, as a time history of the modal amplitudes.

It was found that shapes could be defined in terms of the modes which exhibit significant Spearman rank correlation coefficients to the ratings of the comfort of ingress and egress as assigned by occupants of the vehicles. The coefficients were both positive and negative – the positive coefficients indicate that the subjects found that movements associated with the shape improved the comfort rating whereas the shapes with a negative correlation coefficient decreased the comfort rating. No shapes were found which had a positive correlation coefficient above a null hypothesis significance level of 5% whereas 13 shapes were found with a negative correlation coefficient at a null hypothesis significance level above 5% and 6 shapes above a null hypothesis significance level of 1%.

Whereas the modes are orthogonal by definition, this is not true for the shapes. Fig. 5 shows the alignment between each of the shapes – the darker the shading of the square, the greater the alignment of the mode. The number in each of the squares is the cosine of the angle between the shape vectors in the 18 dimensional space, times 100.

Shape number 18 has the maximum negative correlation coefficient to the comfort rating of $r_s = -0.27$ and is primarily composed of rotation of the medial and lateral ankle rotation and planta/dorsi flexion coupled with lumbar flexion and extension.

However shape vectors 7, 17 and 18 are highly correlated as shown by their high degree of alignment in Fig. 5. Likewise shapes 4 and 5 are highly aligned. Highly aligned shapes are redundant providing little additional information and can be removed from further consideration. There is no reason why the number of modes should equal the number of shapes. The dimensionality of the modes is defined by the variance in the trial data whereas the dimensionality of the shapes is defined by the correlation to the comfort ratings. The smaller number of shapes than modes shows that the shapes have collapsed onto a manifold embedded within the modal space.

The significance of the research in this paper is that it would be advantageous to produce vehicle designs which facilitate and encourage the older occupants to adopt the shapes which exhibit a positive correlation to comfort ratings and discourage movements associated with negative comfort correlations. This can be achieved through the judicious placement of components essential to the ingress/egress motion, for example door handles, sill heights and widths, the travel in seating position and steering wheel travel.

The shapes with the maximum negative correlation to comfort ratings (and hence are the most unfavoured by the subjects) are dominated by medial internal/external rotation and dorsi/planta ankle articulation, lumbar flexion/extension and to a lesser extent lateral ankle dorsi/planta flexion. Therefore vehicle designs for the elderly which reduce the need for these joint movements may be preferred by the older occupants.

The modes and shapes associated with vehicle ingress/egress will be a function of the diversity of the subjects' anthropometry. The literature indicates that with age there is reduced torque and power at the ankle, knee and hip joints (Crowinshield et al., 1978; Judge et al., 1996; Kerrigan et al., 1998; Winter et al., 1990) which affects the sit-stand-sit movement and therefore ingress and egress of vehicles which is consistent with the findings of this study. The current study is biased towards the anthropometry of the older population however studies have looked at the effect of ageing on the sit-stand-sit task measuring different elements of the task and impact on the body (Hesse et al., 1994; Hughes and Schenkman, 1996; Papa and Cappozzo, 2000) and recognise that older people have differing requirements in terms of sitting comfort and the task (Aissaoui and Dansereau, 1999). This will suggests that the calculated shapes are age dependant future research may consider the modification of these fundamental patterns with advancing age. It would be of interest in a future study to investigate the affect of varying body sizes found in alternative populations on the derived modes and shapes.

The coefficients of the amplitudes in the modes and the shapes are calculated as real numbers and hence all joint articulations are implied to occur in-phase with each other. If the method were to be extended to consider complex coefficients, phase shifts between joint movements could be included in the analysis.

5. Conclusions

Poor correlation was observed between the articulations of individual joints and the comfort rating of vehicle I/E. Therefore a multi-joint, whole body analysis procedure was adopted which involved decomposing the body's movement during I/E into a small number of fundamental modes. It was found that the movement could be expressed as a modal superposition of 18 orthogonal modes which contain 98% of the variance of all of the subjects during I/E of all vehicles. The dimensionality of the modal representation was considerably less than the dimensionality which was required to describe the movement using physical degrees of freedom.

Shapes were found which were a linear superposition of the

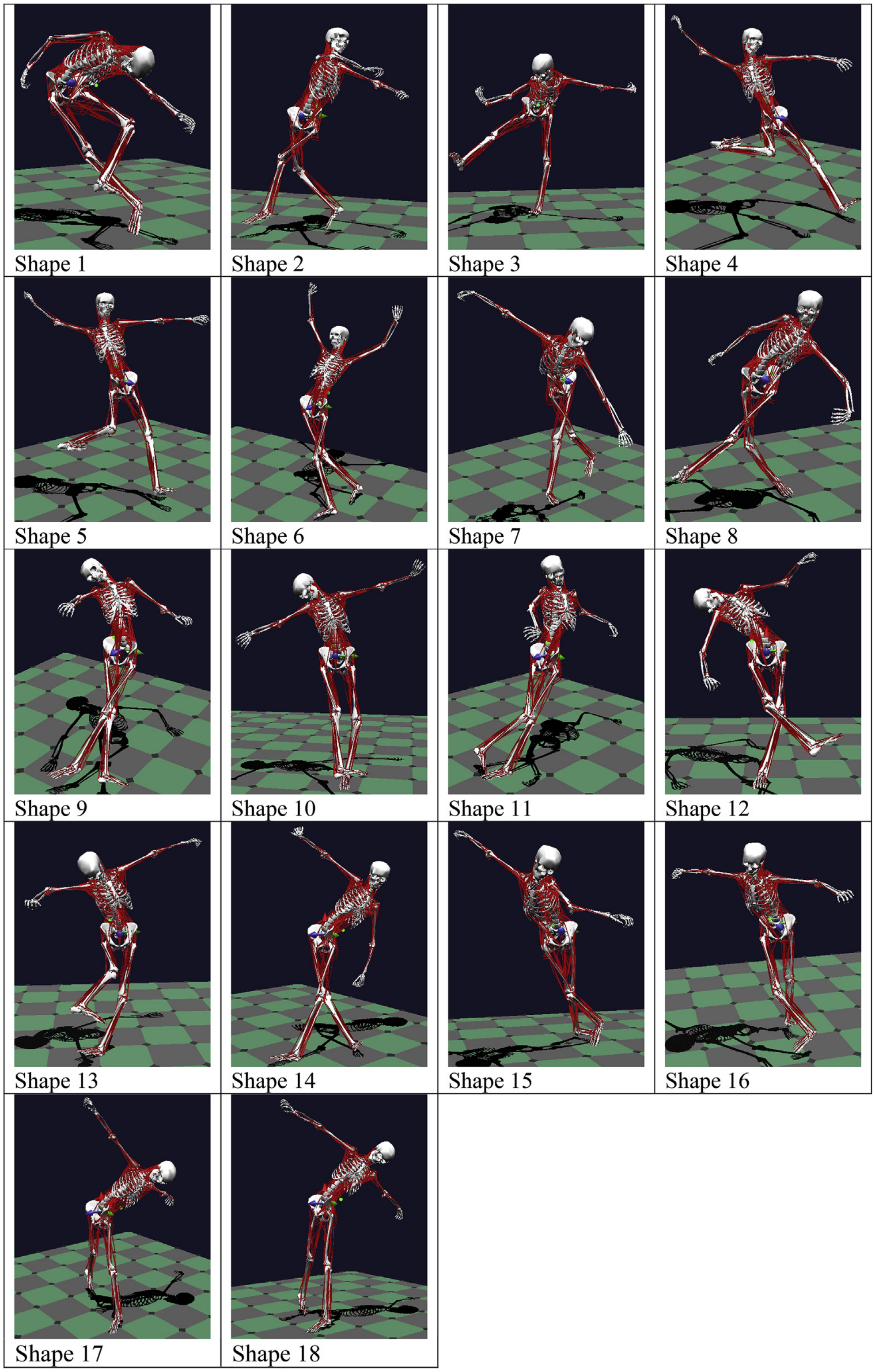

Fig. 4. Shapes optimised for comfort rating correlation.

modes that maximised the correlation to the comfort rating assigned to the ease of I/E for all of the vehicles by the subjects in the study. A null hypothesis significance level below 5% was found for 13 shapes and a null hypothesis significance level below 1% was found for 6 shapes. This indicates that the shapes show a strong correlation to the comfort rating for I/E assigned by the trials' subjects. The majority of the correlation coefficients are negative indicating that the adoption of these shapes during I/E is associated with a decrease in the comfort rating.

An appreciation of body shapes which are associated with a low comfort rating for ingress and egress is an important consideration in the interior design of passenger vehicles. It may be possible to

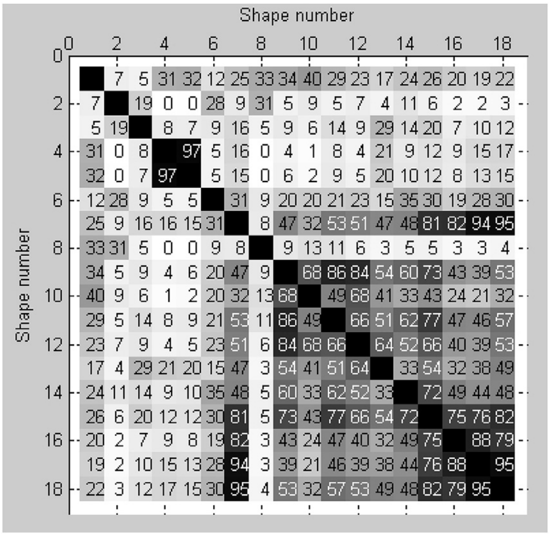

Fig. 5. The alignment of the constitutive shapes.

design internal features to discourage, or eliminate, the adoption of postures which are closely aligned with these undesirable shapes.

The current study only considered older members of the driving population but by designing for the elderly, the younger driver will probably also benefit. In a future study it would be interesting to compare the modes and shapes of older and younger drivers.

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