

Constitutive kinematic modes and shapes during vehicle ingress/egress

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Abstract: 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.

2 November 2015

The Editor
Applied Ergonomics

Dear Sir

Re: Constitutive kinematic modes and shapes during vehicle ingress / egress

I would be most appreciative if you would consider the attached manuscript for publication in Applied Ergonomics. I believe the manuscript contains a novel analysis procedure to decompose vehicle ingress/egress in its constituent modes and then synthesizes these modes to form shapes which correlate with comfort assessments. This method is applicable to the board range of design methodologies including vehicle design and other disciplines where ease of movement is significant.

Regards

James Shippen
Coventry University

Detailed Response to Reviewers

Reviewer #1: My view is that the authors have modified the paper according to reviewers' comments in a good way, improving the clarity and quality of the paper.

Just a small typo to correct (Section 2.0 Materials and Methods): Unit is missing for "1.93".

Units of meters has been included

It seems to be a typo in this sentence ("may" should be "many" I suppose): "The motion does constitute a large component of the walking action but neglects may of the subtleties of gait and would be very impractical."

The typographical error has been corrected

Reviewer #2: All issues and comments have been properly addressed in the modified manuscript.

Many thanks to both reviewers for their constructive comments.

Highlights:

- The motion during ingress/egress is decomposed into multi-joint constituent modes.
- The modes combine to form shapes associated with ingress/egress
- Shapes maximise correlation to ease of ingress/egress.
- Knowledge of comfort shapes are instructive for interior vehicle design.

**Constitutive kinematic modes and shapes
during vehicle ingress / egress**

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Abstract

1 A study was undertaken to investigate the kinematics of older users of passenger
2 vehicles during ingress/egress and to seek correlations between their movement and
3 comfort rating assigned by the subjects to the ease of vehicle ingress and egress. A
4 principal component analysis was performed on the subjects' kinematics to identify
5 the underlying modes of movement employed by the subjects. It was found that a
6 small number of modes could describe the movements of all the subjects across all of
7 the vehicles. Within the subspace defined by the modal vectors, shapes were found
8 which correlated to the comfort rating for ease of ingress and egress which the
9 subjects had assigned to each of the cars. Knowledge of these shapes which
10 correspond to good and poor ingress and egress will be useful to the designers of
11 interiors and exteriors of passenger vehicles for the older person. It is recommended
12 that vehicle designs for the older person should attempt to avoid body positions which
13 require excessive ankle articulation and lumbar flexion/extension during ingress and
14 egress.
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17
18

19 **Keywords:** Ingress/egress, principal component analysis, comfort, motion analysis,
20 older users, vehicles, cars, ergonomics
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1.0 Introduction

26 Comfort is a subjective concept which is difficult to objectively define and measure as
27 there is no universally accepted operational definition of comfort (Leuder 1983).
28 Many researchers have adopted the definition of comfort as being “the absence of
29 discomfort” (Hertzberg 1972) as it is more straightforward to quantify discomfort
30 than to measure comfort. Comfort and discomfort can best be understood under a
31 theory of complexity since it emerges from a chain of interaction processes between
32 the human and several elements of a system (Da Silva et al 2012). The perception of
33 comfort and discomfort is a multifactorial sensation which is a function of numerous
34 factors mutually interacting and interacting with the subject in a complex manner.
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39 In recent years, car manufacturers have increased their interest in vehicle comfort in
40 general and ease of ingress/egress (I/E) in particular. To study ease of use,
41 automobile manufacturers have sought validation using physical mock-ups of vehicles
42 and subjective judgements given by subjects to correlate with vehicle dimensions
43 (Tessier 2000).
44
45

46 However with a growing ageing population and an increased number of people
47 maintaining an active lifestyle well into their 80s, it is suggested that the design of
48 vehicles would benefit from a clear understanding of the limitations related to age-
49 associated reductions in physical mobility (Berman et al 1988). According to Smith
50 and Sethi (1975), joint flexibility declines by approximately 25% in older adults.
51 These age-related restrictions occur naturally within an ageing musculoskeletal
52 system, for example joint range of motion decreases with age and reduction in joint
53 flexibility can lead to less efficient movement patterns (Daley and Spinks 2000,
54 Vandervoort 2002).
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58 Sarcopenia also occurs with the ageing process and specifically refers to loss of
59 skeletal muscle mass. All men and women experience some degree of sarcopenia
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1 (defined as losses greater than 2 SD below the mean for young healthy controls)
2 (Doherty 2003); with prevalence ranging from 13 to 24% in persons aged 65 to 70
3 years; and over 50% for those older than 80 years (Baumgartner et al. 1998).

4
5 Rising from any chair is a biomechanically demanding task for the older person which
6 requires co-ordination, balance, adequate mobility and strength (Riley et al 1997,
7 Riley et al 1991, Ikeda et al 1991). Research suggests a range of biomechanical
8 factors affect the ability to rise from a seat such as knee torque, horizontal and vertical
9 linear momentum, balance, choice of seat rise strategy and upper and lower extremity
10 strength (Hughes, Weiner et al 1994, Janssen et al 2002) and older adults have been
11 found to increase hip flexion and optimize knee joint velocities whilst rising from a
12 chair (Schenkman et al 1990, Hughes and Schenkman 1996).

13
14
15
16 These difficulties are exacerbated during ingress/egress of a vehicle for an older
17 person (Robert et al 2014). A complete description of the joint loads occurring during
18 I/E motions is not currently available (Robert et al 2014). Few studies have reported
19 on the I/E movement (Menceur et al 2008) although existing studies of I/E movement
20 have focussed on healthy able-bodied people (Giacomin and Quattrocchio 1997,
21 Lestrelin and Trasbot 2005, Lempereur et al 2005).

22
23
24 However, vehicle accessibility and meeting physical limitations related to age is a key
25 vehicle selection criterion for the older driver (Zhan et al 2013) and therefore
26 fulfilling the requirement of ease of use during ingress/egress of vehicles is of
27 commercial, as well as social, importance. It was therefore considered necessary to
28 analyse the movement during I/E of vehicles by the older person and to consider the
29 influence on I/E ease of use comfort levels of movement patterns adopted by the older
30 person.
31
32

33 34 35 **2.0 Materials and Methods**

36 The movement of 30 subjects (17 female, 13 male) during ingress and egress into 4
37 vehicles was measured. The age range of the subjects was 55 to 69 years with a
38 mean age of 62 years and standard deviation of 4.2 years. The weight range of the
39 subjects was 61kg to 120kg with a mean weight of 79kg and standard deviation of
40 18.2kg. The height range was 1.52m to 1.93m with a mean of 1.63m and standard
41 deviation of 0.073m.
42
43

44
45 The ingress, seated posture and egress of the subjects was measured using the
46 magneto-inertial Xsens MVN Awinda system consisting of 17 wireless motion
47 tracking sensors. Each sensor contains 3 orthogonal linear accelerometers and 3
48 orthogonal gyroscopes. Angular drift about horizontal axes was eliminated by
49 sensing the Earth's gravity and angular drift about the vertical axis was eliminated by
50 using a magnetometer to sense the direction of the Earth's magnetic field.
51
52

53
54 Translational drift is more difficult to eliminate using an inertial measurement based
55 system as there is, generally, no external reference. By default, the Xsens assumes a
56 non-slip foot condition for the lower foot to remove drift in the horizontal plane and
57 the Awinda sensors incorporate a barometer in each unit which can supposedly detect
58 changes in altitude. The non-slip foot condition of the lower foot is not always valid,
59 indeed the current study contains a situation when this assumption is violated, ie when
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1 the subject is seated in the vehicle and the feet are being lifted into the vehicle and the
2 accuracy and repeatability of the altitude measurements are unknown. However for
3 this study the absolute location, or even translational movements are not of
4 significance but only the joint articulations and hence translational drift will not affect
5 the results nor conclusions.
6

7 Xsens's MVN Studio software was used for the data capture. During the trial, the
8 sensors attached to subjects were sampled at 60Hz via a wireless interface and data
9 stored on an i7 laptop personal computer.
10

11 A subject wearing the MVN Awinda system is shown in figure 1. The sensors are the
12 small matchbox-sized boxes attached around the body. The sensors were attached to
13 the subjects at the location listed in table 1.
14
15

16 The vehicles used for the trials were large family cars (British market segment) / mid-
17 size car (American market segment). Prior to the ingress/egress trials the subjects
18 were instructed to adjust the seat and steering wheel positions to suit their driving
19 style. The subjects were then instructed to open the vehicles driver's door, enter the
20 vehicle at their own pace and sit in the driver's seat. When the subject had been
21 seated in the driver's seat for approximately 3 seconds they were instructed to egress
22 the vehicle which necessitated opening the driver's door and to close the door after
23 their egression. The subject then moved to the next vehicle and continued until all 4
24 vehicles had been ingressed and egressed. The order in which the subjects
25 encountered the vehicles was the same for all subjects; this was determined by the
26 placement of the vehicles within the laboratory.
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31 Between ingressing and egressing each vehicle, the sensors were re-calibrated to
32 remove drift and motion artefacts resulting from any slippage of the sensors across the
33 body. If there were any large movements of the sensors across the subjects' body
34 during the trials, for example due to an impact contact with the vehicle structure, the
35 sensors were repositioned before calibration and the trial repeated.
36
37
38

39 Immediately following the biomechanical trials, all of the subjects were asked to rate
40 the ease of ingress and egress of each vehicle. The subjects were asked to assess the
41 ease of ingress / egress based on an anatomical basis (eg individual joint articulation)
42 and temporally (eg the moment of maximum comfort/discomfort during the
43 ingress/egress event) but this was found to be confusing for the subjects and difficult
44 to quantify. Therefore the subjects were asked to assess the ease of ingress/egress
45 throughout the action on a scale of 1 (poor performance) to 5 (good performance).
46
47
48

49 It was assumed that the movement of the subjects could be represented by the linear
50 superposition of a number of fundamental "modes" of motion where the number of
51 modes is significantly less than the total number of degrees of freedom of the subject.
52
53

54 As an example of the concept of decomposing movements into fundamental modes,
55 consider walking gait. Walking gait could be considered to be anti-phase swinging of
56 straight legs. The motion does constitute a large component of the walking action but
57 neglects many of the subtleties of gait and would be very impractical. Next introduce
58 another movement which consists of some knee flexion with ankle dorsiflexion. The
59 combined action of leg swing and knee/ankle shape would enable foot clearance from
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1 the ground during swing phase which would improve the gait relative to simple leg
2 swinging but would still lack the finesse of real human gait. Therefore add more and
3 more patterns of joint articulations until a motion indistinguishable from true gait is
4 achieved. These patterns are the fundamental modes of gait. It is important to note
5 that each of these modes typically contain articulations of numerous joints, all moving
6 in phase.
7

8 This paper considers applying this deconstructive approach to analyse ingress/egress
9 of vehicles and the task of identifying comfort rating versus movement correlation.
10 This was undertaken by the identification of the appropriate linear combination of the
11 modes of motion associated with vehicle ingress/egress which maximises their
12 correlation to comfort assessments provided by the trials' subjects.
13
14

15 **3.0 Theory / Calculation**

16 It will be assumed that the movement of the human body can be represented as a
17 multi-rigid-body mechanism with $6 + 3*N$ physical degrees of freedom where N is
18 the number of joints each possessing 3 degrees of freedom. However rotation of
19 some of these degrees of freedom may be restricted to virtually zero due to local
20 anatomy. For example, the elbow can be modelled, for most applications, as a
21 revolute hinge joint which releases the flexion/extension degree of freedom and the
22 movement of the internal/external rotation and varus/valgus degrees of freedom
23 being constrained to zero articulation. Six degrees of freedom are associated with the
24 translations and rotations associated with the root segment, which was the pelvis for
25 the current study. However human anatomy and physiology implies that these
26 physical degrees of freedom do not operate independently, for example during gait
27 hip, knee and ankle articulations follow a repeatable functional relationship. This
28 relationship can be expressed as a constraint equation between the physical degrees of
29 freedom. If the movement pattern has C constraint equations, the total number of
30 degrees of freedom reduces to $6 + 3*N - C$.
31
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36 All of the physical degrees of freedom can be removed from the motion of a
37 mechanism by the introduction of generalised degrees of freedom and constraint
38 equations which relate the displacements of the physical degrees of freedom to the
39 generalised degrees of freedom. The constraint equations take the form of a modal
40 matrix where the columns of the matrix describe the shapes of the modes in terms of
41 the physical degrees of freedom.
42
43
44

$$45 \quad \mathbf{u} = \psi \cdot \zeta$$

46 where
47 \mathbf{u} is the vector of physical degrees of freedom (eg joint
48 articulations)
49 ψ is a matrix of constraint equations – the modal matrix
50 ζ is a vector of modal contributions of the generalised degrees
51 of freedom associated with the shapes defined in the modal
52 matrix
53
54
55

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

3
4 If the mechanism's position changes with time the above relationship becomes:

$$5 \quad \mathbf{u}(\mathbf{t}) = \psi \cdot \zeta(\mathbf{t})$$

6
7
8 where it is assumed that the modal matrix is time invariant. The columns of the
9 matrix $\mathbf{u}(\mathbf{t})$ represent the displacement of the physical degrees of freedom at
10 subsequent times and the columns of the matrix $\zeta(\mathbf{t})$ represent the contributions of the
11 modal degrees of freedom at subsequent times.
12
13

14 The task in formulating ψ is then to identify an orthogonal set of modal vectors which
15 retains a total variance in the data in excess of a predefined threshold. Principal
16 component analysis (Hubert et al 2005) was used for the calculation of the modal
17 matrix ψ as implemented in MATLAB (Mathworks Inc, Natick, MA) eliminating
18 modal components that contribute less than 2% to the total variation in the data set.
19
20

21
22 $\mathbf{u}(\mathbf{t})$, is available from physical measurement using the motion capture system and
23 hence the modal contributions, $\zeta(\mathbf{t})$, can be calculated from:
24

$$25 \quad \psi^T \cdot \mathbf{u}(\mathbf{t}) = \psi^T \cdot \psi \cdot \zeta(\mathbf{t})$$

26
27
28 As ψ is an orthogonal matrix this reduces to:

$$29 \quad \psi^T \cdot \mathbf{u}(\mathbf{t}) = \zeta(\mathbf{t})$$

30
31
32 from which the modal contributions can be calculated as the matrix $\mathbf{u}(\mathbf{t})$ is available
33 from the motion captured data.
34
35

36
37 The modal matrix, ψ , defines an orthogonal base of a sub-space within the space
38 traversed by the physical degrees of freedom whilst retaining 98% of the variance of
39 the observed motion. Therefore operating within this reduced dimensionality can
40 offer considerable computational advantages.
41
42

43 Modes are mathematical abstractions of the principal component analysis with no
44 reference; the modes are the building blocks which can be assembled to create the
45 posture of the subject. However the modes define a compact basis for representing
46 the observed postures. Nor do modes correspond to the comfort ratings provided by
47 the subjects, however it may be possible to construct shapes from a linear
48 superposition of these modes which do possess a significant correlation to comfort
49 ratings.
50
51

52
53 To this end shapes were constructed, defined in the orthogonal base of the modal
54 matrix, which displayed maximal correlation to the vehicles' comfort ratings.
55

56 Let $\mathbf{S} = \phi \cdot \psi$
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1 where S is the shape matrix whose columns represent shapes which
2 maximise the correlation of the shape contribution vector to
3 the comfort rating. S is not necessarily an orthogonal matrix
4 ϕ is the shape contribution matrix defining the superposition of
5 the modes within the shape matrix. ϕ is not necessarily an
6 orthogonal matrix
7

8 The contributions of these shapes to the observed movement can be calculated from:
9

$$10 \quad \theta(\mathbf{t}) = S^T \cdot \mathbf{u}(\mathbf{t}) \quad (1)$$

11 where $\theta(\mathbf{t})$ is the contributions of the shapes to the observed motions.
12

13 Because of the dimensional reduction of the modal degrees of freedom substitution,
14 the sub-volume can be efficiently searched to identify the shapes which maximises the
15 correlation and the ease of comfort ratings for I/E assessed by the subjects.
16

17 Spearman rank correlation coefficients (Lehman 2005) were calculated between the
18 shapes and the ease of comfort ratings used as this procedure can compare the
19 discrete, qualitative assessment of the comfort rating questionnaire against the
20 continuous, quantitative measurement of biomechanical variables.
21
22

23 To calculate the shapes which maximise the magnitude of the correlation coefficients,
24 the following procedure was iteratively applied:
25
26

27
28 Step 1: Calculate the shape contribution to the observed time history of physical
29 degrees of freedom from equation (1) assuming the shapes are equal to the
30 modes.
31

32 Step 2: Calculate the Spearman rank correlation coefficients between the
33 maximum change in amplitudes of the shape contributions and the ease of
34 I/E comfort ratings as assessed by all of the subjects to all of the vehicles.
35

36 For each shape

37 Step3: Perturbate the shape by sequentially adding one of the modes multiplied
38 by a scaling factor.

39 Step 4: Calculate the magnitude of the Spearman rank correlation coefficients
40 between the maximum change in amplitude of this perturbed shape's
41 contribution and the I/E comfort rating.
42

43 Step 5: If the correlation decreased as a result of the perturbation:
44 disregard this perturbation.

45 Else if the correlation increased as a result of the perturbation:
46 update the shape to include this perturbation.
47

48 Step 6: Repeat from step 3 for all of the modes.

49 Step 7: Decrement the scaling factor and repeat from step 3 unless the change in
50 the magnitude of the correlation co-efficient is less than a pre-defined
51 threshold.
52

53 Step 8: Repeat for all shapes.
54
55

56 4.0 Results

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

3
4 For the subjects employing a left-leg-first strategy, ingress was considered to start
5 when the subject adopted a single leg stance and finished when both heels contacted
6 the floor of the vehicle. The egress commenced when one foot departed the vehicle
7 floor and finished when a two foot stance on the external floor was adopted.
8

9
10 For the subjects employing a two-legs-out strategy, the ingress was considered to start
11 when knee flexion exceeded 15 degrees and finished when both heels contacted the
12 floor of the vehicle. The egress commenced when one foot departed the vehicle floor
13 and finished when a two foot stance on the external floor was adopted.
14

15
16 Time histories of the following 42 physical degrees of freedom were sampled at 60
17 frames per second:

18 Neck Joint

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

20 Right/Left Shoulder

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

22 Right/Left Elbow

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

24 Right/Left Wrist

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

26 Lumbar Joint

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

28 Right/Left Hip

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

30 Right/Left Knee

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

32 Right/Left Ankle

33 Abduction /Adduction; Internal /External Rotation; Dorsiflexion /Plantarflexion
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35
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39 The musculoskeletal analysis package BoB (Biomechanics of Bodies) (Shippen and
40 May 2012) was used to undertake the principal component analysis (PCA) of the time
41 histories of physical degrees of freedom. The PCA returns the constituent modes of
42 the time histories and the modal contributions throughout the time history therefore
43 whilst the differing lengths of the trials affect the modal contribution histories it does
44 not affect the modes. The PCA transform retained 98% of the variance in the original
45 data set which resulted in a dimension reduction to 18 orthogonal principal
46 component vectors. The modes which were calculated by the PCA are shown in
47 figure 2. The relative joint articulations are of significance within the mode and not
48 the absolute magnitude of any joint angle hence in figure 2 the mode is illustrated
49 with the maximum joint articulation set to 60 degrees.
50
51
52

53 These modes are similar in form to the results of a Fourier analysis of a waveform.
54 Any waveform can be decomposed into the linear superposition of an orthogonal base
55 defined by harmonic sine waves; in this analogy, the modes calculated by the PCA
56 correspond to the harmonic sine waves.
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1 Within the orthogonal base defined by these modes, the sub-space was searched to
2 create shapes as a linear combination of the modes which maximise the correlation
3 between these shapes in the observed movements and the comfort ratings as described
4 in the Theory/Calculation section.
5

6 Figure 3 shows the Spearman rank correlation coefficient (Sockloff and Edney 1972)
7 between each of the shapes and the comfort ratings ordered into decreasing
8 correlation coefficient. Also shown on figure 3 are the correlation coefficients
9 corresponding to a significance level for the null hypothesis of 5% and 1% for a
10 sample size $N=120$ (30 subjects, 4 vehicles). The shapes which maximise the comfort
11 rating correlations are shown in figure 4. Shape 1 has the maximum Spearman rank
12 correlation coefficient of 0.141, shape 2 has the next largest correlation of 0.0620
13 through to shape 18 which has a correlation coefficient of -0.27 .
14
15

16 Each of these shapes are described as the relative articulations of each of the joints –
17 the absolute size of the articulations of each of the joints within the shape has no
18 meaning as it is only when these shapes are combined to recreate the observed motion
19 that the magnitude of the shape has a physical significance. Table 1 lists the 5 largest
20 relative joint articulations in each of these shapes. Medial (Med) refers to the joint
21 closest to the centreline of the vehicle and lateral (Lat) refers to the joint furthest from
22 the vehicle's centreline.
23
24
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26
27

28 **5.0 Discussion**

29 The magneto-inertial motion capture system used was found to be suitable for the task
30 of measuring the movement of the subjects during the ingress/egress activity. The
31 sensors which were used for the trials introduced little inconvenience to the subjects
32 and were rapidly attached to the subjects' bodies. There was an occasional collision
33 between the sensors and the vehicle but the real-time monitoring of the data made
34 identification of these events easy to see and the trial was immediately repeated. The
35 collected data was clean and did not require further processing. Translational drift
36 was observed, particularly in the vertical direction, but this was not significant to the
37 study as joint articulation was of primary interest.
38
39
40

41 The study commenced by researching the correlation between individual joint angles
42 and comfort ratings but poor correlation coefficients were found across the body and
43 no correlation coefficient was found in excess of a significance level of 5%. This
44 suggested to the researchers that comfort during ingress/egress was being assessed by
45 the subjects as a multi-joint phenomenon rather than on an individual joint basis.
46
47

48 A principle component analysis of the joint articulations during ingress and egress
49 indicate that a sub-space with a dimensionality of 18 contained 98% of the variance of
50 the joint articulations.
51
52

53 The lower the dimensionality of the movement, the more simplistic is the motion
54 which is observed (Bronner, Shippen 2015). By way of an example, consider the gait
55 example described above; if gait were to be described as anti-phase leg swinging it
56 would have a dimensionality of 1, include the knee flexion/ankle dorsiflexion and the
57 dimensionality increases to 2, a recognisably human gait would have a dimensionality
58 of about 10. The existence of the model sub-space does not imply that the subject
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1 will exhibit any of these modes during the trial, but that the observed motion is a
2 linear superposition of these underlying modes. The modal sub-space also
3 demonstrates that the joint movements were not operating independently but rather as
4 a combination of fundamental shapes. These modes can be described by the relative
5 size of the joint articulation occurring within the modes and the original motion can
6 be expressed, in a concise manner, as a time history of the modal amplitudes.
7

8 It was found that shapes could be defined in terms of the modes which exhibit
9 significant Spearman rank correlation coefficients to the ratings of the comfort of
10 ingress and egress as assigned by occupants of the vehicles. The coefficients were
11 both positive and negative – the positive coefficients indicate that the subjects found
12 that movements associated with the shape improved the comfort rating whereas the
13 shapes with a negative correlation coefficient decreased the comfort rating. No
14 shapes were found which had a positive correlation coefficient above a null
15 hypothesis significance level of 5% whereas 13 shapes were found with a negative
16 correlation coefficient at a null hypothesis significance level above 5% and 6 shapes
17 above a null hypothesis significance level of 1%.
18
19
20
21

22 Whereas the modes are orthogonal by definition, this is not true for the shapes.
23 Figure 5 shows the alignment between each of the shapes – the darker the shading of
24 the square, the greater the alignment of the mode. The number in each of the squares
25 is the cosine of the angle between the shape vectors in the 18 dimensional space,
26 times 100.
27
28

29 Shape number 18 has the maximum negative correlation coefficient to the comfort
30 rating of $r_s = -0.27$ and is primarily composed of rotation of the medial and lateral
31 ankle rotation and planta/dorsi flexion coupled with lumbar flexion and extension.
32
33

34 However shape vectors 7, 17 and 18 are highly correlated as shown by their high
35 degree of alignment in figure 5. Likewise shapes 4 and 5 are highly aligned. Highly
36 aligned shapes are redundant providing little additional information and can be
37 removed from further consideration. There is no reason why the number of modes
38 should equal the number of shapes. The dimensionality of the modes is defined by
39 the variance in the trial data whereas the dimensionality of the shapes is defined by
40 the correlation to the comfort ratings. The smaller number of shapes than modes
41 shows that the shapes have collapsed onto a manifold embedded within the modal
42 space.
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46 The significance of the research in this paper is that it would be advantageous to
47 produce vehicle designs which facilitate and encourage the older occupants to adopt
48 the shapes which exhibit a positive correlation to comfort ratings and discourage
49 movements associated with negative comfort correlations. This can be achieved
50 through the judicious placement of components essential to the ingress/egress motion,
51 for example door handles, sill heights and widths, the travel in seating position and
52 steering wheel travel.
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56 The shapes with the maximum negative correlation to comfort ratings (and hence are
57 the most unfavoured by the subjects) are dominated by medial internal/external
58 rotation and dorsi/planta ankle articulation, lumbar flexion/extension and to a lesser
59 extent lateral ankle dorsi/planta flexion. Therefore vehicle designs for the elderly
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1 which reduce the need for these joint movements may be preferred by the older
2 occupants.

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4 The modes and shapes associated with vehicle ingress/egress will be a function of the
5 diversity of the subjects' anthropometry. The literature indicates that with age there is
6 reduced torque and power at the ankle, knee and hip joints (Crowinshield et al 1978,
7 Judge et al 1996, Kerrigan et al 1998, Winter et al 1990) which affects the sit-stand-sit
8 movement and therefore ingress and egress of vehicles which is consistent with the
9 findings of this study. The current study is biased towards the anthropometry of the
10 older population however studies have looked at the effect of ageing on the sit-stand-
11 sit task measuring different elements of the task and impact on the body (Hesse et al.,
12 1994; Hughes and Schenkman, 1996, Papa and Cappozzo 2000) and recognise that
13 older people have differing requirements in terms of sitting comfort and the task
14 (Aissaoui and Dansereau 1999). This will suggests that the calculated shapes are age
15 dependant future research may consider the modification of these fundamental
16 patterns with advancing age. It would be of interest in a future study to investigate
17 the affect of varying body sizes found in alternative populations on the derived modes
18 and shapes.
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23 The coefficients of the amplitudes in the modes and the shapes are calculated as real
24 numbers and hence all joint articulations are implied to occur in-phase with each
25 other. If the method were to be extended to consider complex coefficients, phase
26 shifts between joint movements could be included in the analysis.
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30 **6.0 Conclusions**

31 Poor correlation was observed between the articulations of individual joints and the
32 comfort rating of vehicle I/E. Therefore a multi-joint, whole body analysis procedure
33 was adopted which involved decomposing the body's movement during I/E into a
34 small number of fundamental modes. It was found that the movement could be
35 expressed as a modal superposition of 18 orthogonal modes which contain 98% of the
36 variance of all of the subjects during I/E of all vehicles. The dimensionality of the
37 modal representation was considerably less than the dimensionality which was
38 required to describe the movement using physical degrees of freedom.
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42 Shapes were found which were a linear superposition of the modes that maximised
43 the correlation to the comfort rating assigned to the ease of I/E for all of the vehicles
44 by the subjects in the study. A null hypothesis significance level below 5% was found
45 for 13 shapes and a null hypothesis significance level below 1% was found for 6
46 shapes. This indicates that the shapes show a strong correlation to the comfort rating
47 for I/E assigned by the trials' subjects. The majority of the correlation coefficients are
48 negative indicating that the adoption of these shapes during I/E is associated with a
49 decrease in the comfort rating.
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53 An appreciation of body shapes which are associated with a low comfort rating for
54 ingress and egress is an important consideration in the interior design of passenger
55 vehicles. It may be possible to design internal features to discourage, or eliminate, the
56 adoption of postures which are closely aligned with these undesirable shapes.
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1 The current study only considered older members of the driving population but by
2 designing for the elderly, the younger driver will probably also benefit. In a future
3 study it would be interesting to compare the modes and shapes of older and younger
4 drivers.
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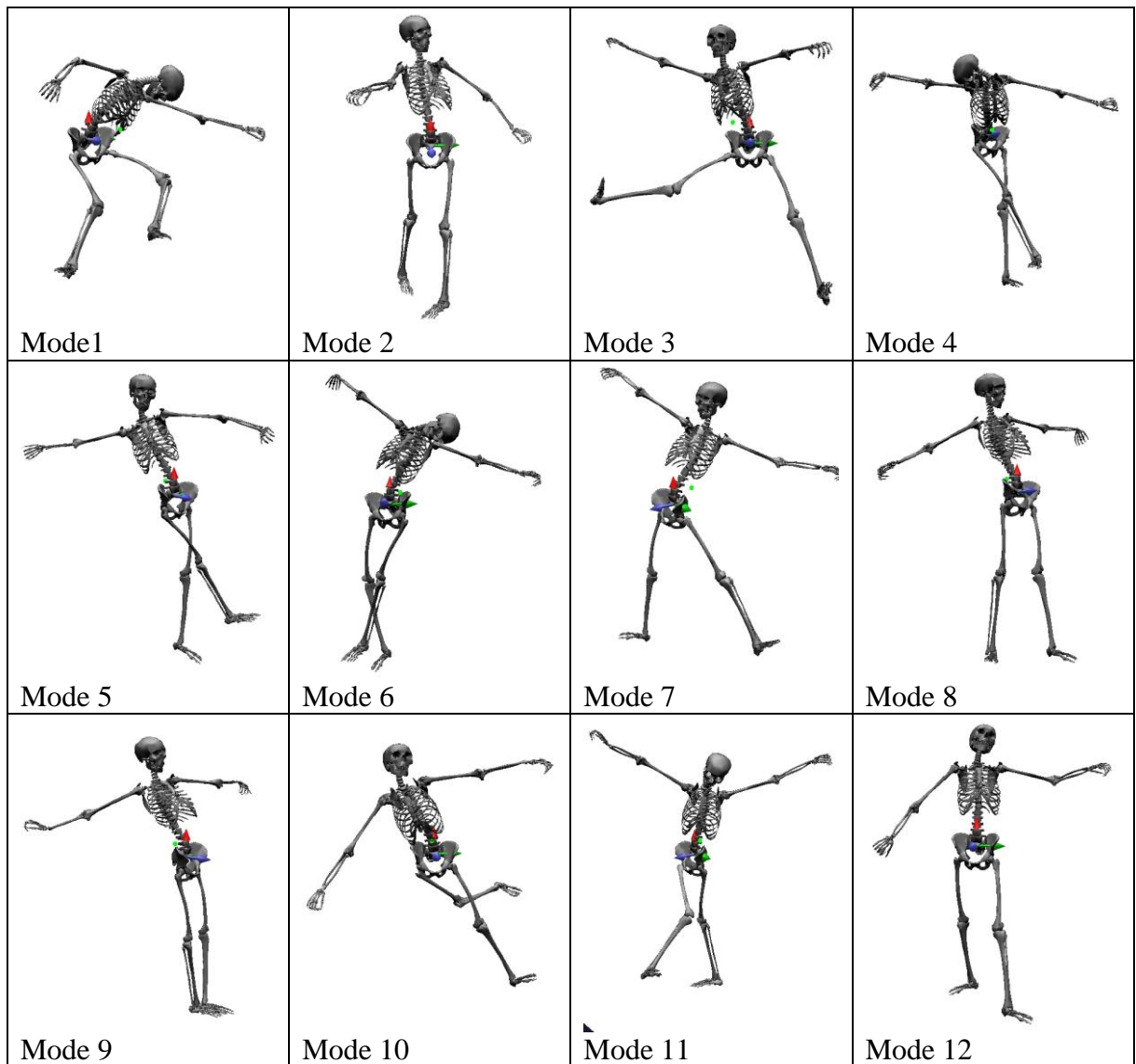
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Figure 1: Magneto-inertial motion capture system attached to a subject – the sensors are the small “matchboxes” attached to the subject



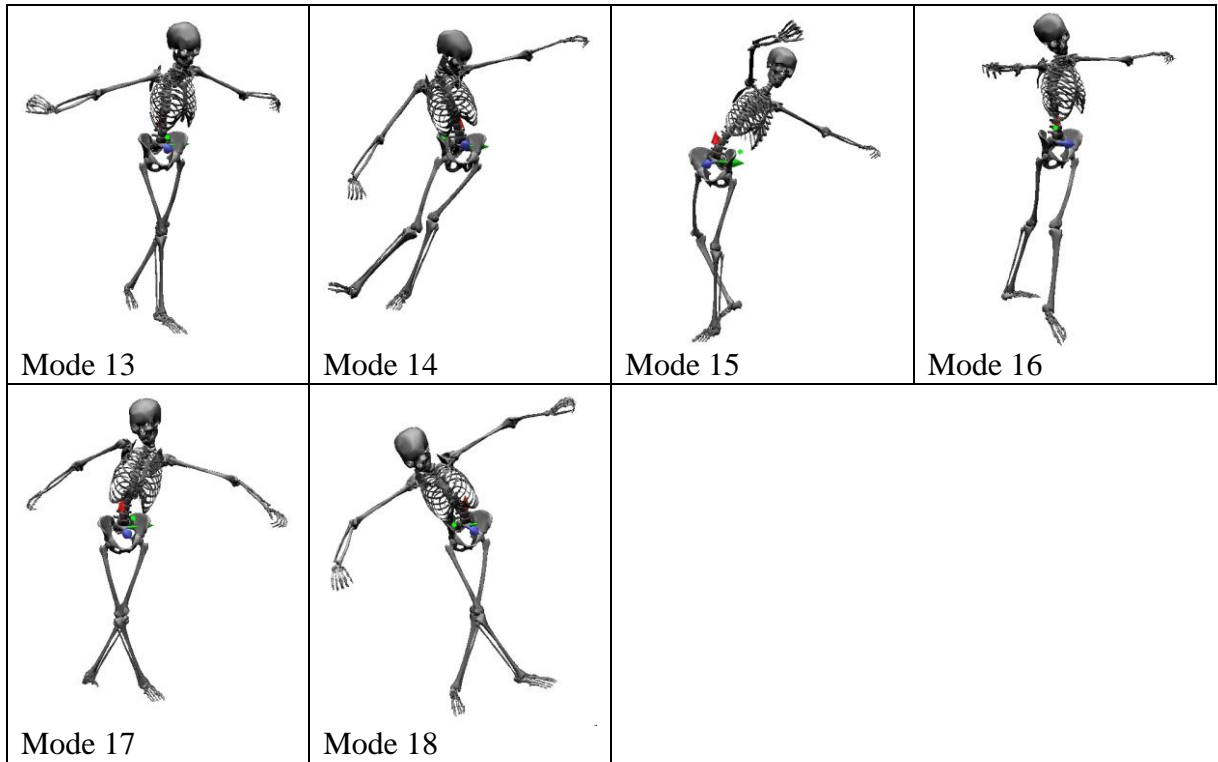


Figure 2: The mode shapes forming an orthogonal base

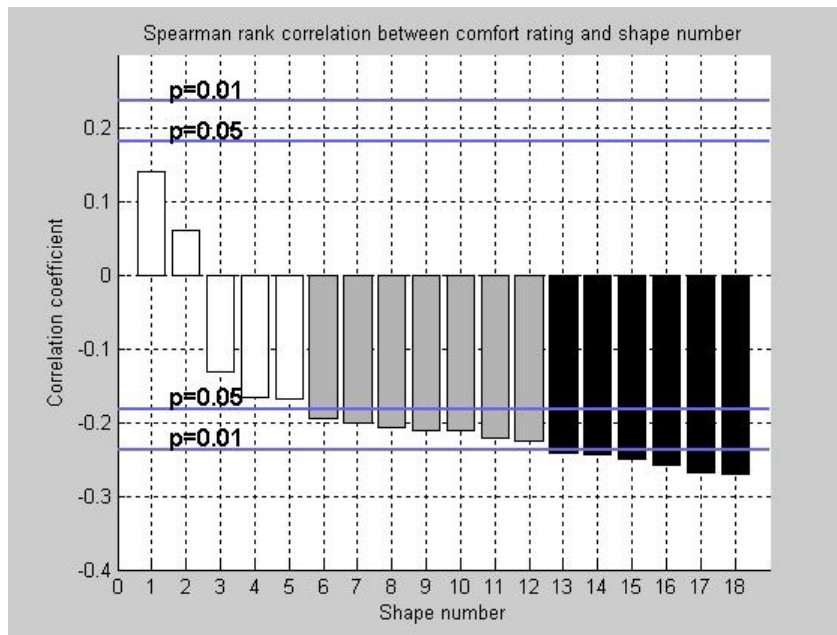
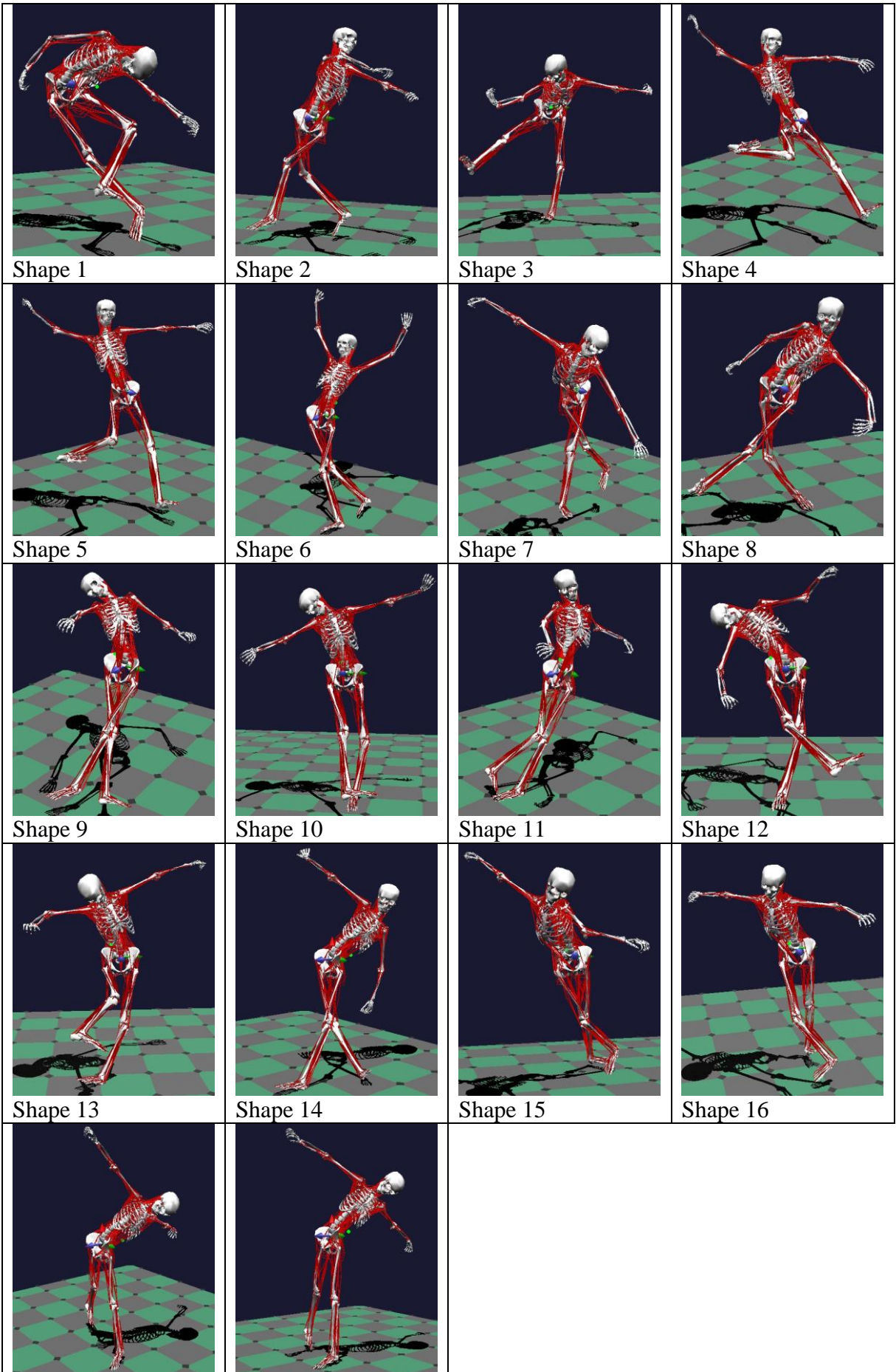


Figure 3: Correlation between comfort rating and optimised shapes



Shape 17

Shape 18

Figure 4: Shapes optimised for comfort rating correlation

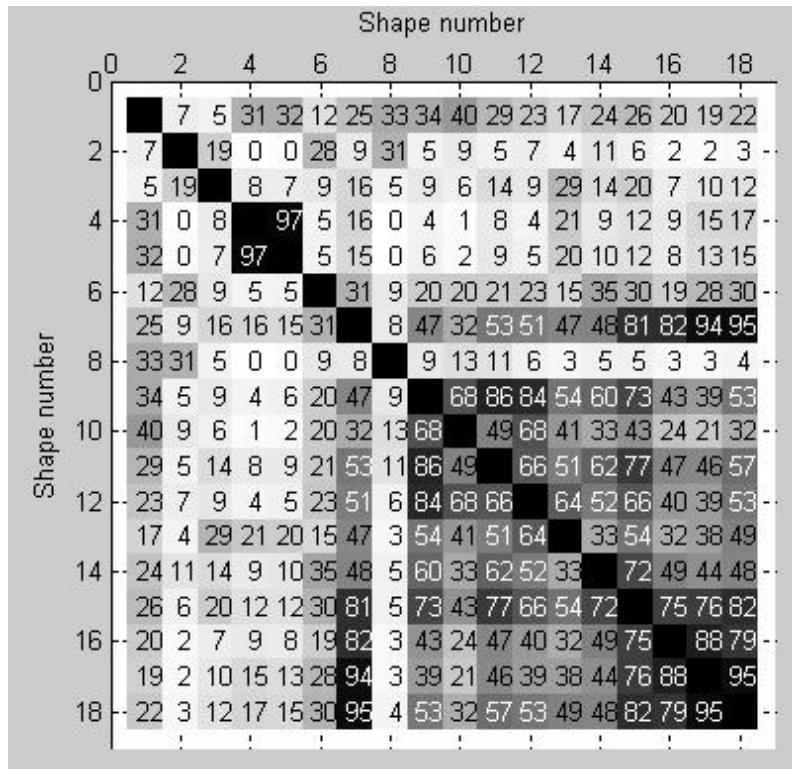


Figure 5: The alignment of the constitutive shapes

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

Table 1: Location of sensors placed on the body

| Shape | Movement 1 | Movement 2 | Movement 3 | Movement 4 | Movement 5 |
|-------------------------------|------------------------------------|--|---|---|---|
| 1 $r = 0.141$ Degrees | Lat wrist Flex/Extension 60 | Lat elbow Pro/Supination 52.769 | Med shoulder Ab/Adduction 52.6915 | Lat shoulder Ab/Adduction 46.6106 | Med wrist Flex/Extension 45.0156 |
| 2 $r = 0.062$ Degrees | Lat wrist Pro/Supination 60 | Lat knee Rotation 52.5741 | Lat shoulder Rotation 48.2938 | Lumbar Flex/Extension 45.5633 | Med shoulder Rotation 36.8745 |
| 3 $r = -0.131$ Degrees | Med knee Rotation 60 | Lat wrist Pro/Supination 59.0037 | Med hip Flex/Extension 54.6266 | Med wrist Pro/Supination 50.0164 | Lumbar Rotation 43.817 |
| 4 $r = -0.166$ Degrees | Lat elbow Flex/Extension 60 | Med hip Ab/Adduction 50.2631 | Med elbow Flex/Extension 49.624 | Med knee Ab/Adduction 42.1757 | Lat elbow Pro/Supination 38.2652 |
| 5 $r = -0.168$ Degrees | Lat elbow Flex/Extension 60 | Med elbow Flex/Extension 53.6643 | Med hip Ab/Adduction 33.457 | Med knee Ab/Adduction 31.5703 | Lat elbow Pro/Supination 30.4298 |
| 6 $r = -0.195$ Degrees | Lat knee Flex/Extension 60 | Med knee Flex/Extension 42.9608 | Lat elbow Flex/Extension 41.6152 | Lat ankle Dorsi/Planta 37.7741 | Med wrist Pro/Supination 37.4061 |
| 7 $r = -0.201$ Degrees | Med ankle Rotation 60 | Lumbar Flex/Extension 48.2779 | Med ankle Dorsi/Planta 47.7243 | Med knee Rotation 44.8343 | Lat ankle Dorsi/Planta 41.285 |
| 8 $r = -0.206$ Degrees | Med shoulder Ab/Adduction 60 | Lat wrist Flex/Extension 50.0767 | Lat hip Flex/Extension 49.1145 | Lat ankle Ab/Adduction 40.45 | Lat shoulder Rotation 38.1979 |
| 9 $r = -0.210$ Degrees | Lat elbow Ulnar/Radial 60 | Med ankle Rotation 52.5541 | Med shoulder Flex/Extension 48.8741 | Med shoulder Rotation 42.2428 | Lat elbow Pro/Supination 34.5871 |
| 10 $r = -0.211$ Degrees | Lat wrist Flex/Extension 60 | Med ankle Rotation 46.5376 | Med wrist Flex/Extension 32.0503 | Neck Flex/Extension 30.4351 | Med shoulder Rotation 30.1119 |
| 11 $r = -0.220$ Degrees | Lat elbow Ulnar/Radial 60 | Lat elbow Pro/Supination 59.2692 | Lumbar Flex/Extension 50.0241 | Med ankle Rotation 46.9415 | Med shoulder Flex/Extension 38.7324 |
| 12 $r = -0.224$ | Med ankle Rotation | Lat elbow Ulnar/Radial | Lat ankle Dorsi/Planta | Med knee Flex/Extension | Neck Lateral Bending |

| | | | | | |
|-----------------------------|-----------------------------------|---------------------------------------|--------------------------------------|--|--|
| Degrees | 60 | 58.8646 | 49.8953 | 48.5324 | 36.9639 |
| 13 r = -0.242 Degrees | Med ankle Rotation 60 | Med knee Rotation 53.3202 | Med hip Rotation 47.8583 | Med knee Flex/Extension 33.4751 | Lat elbow Pro/Supination 23.9173 |
| 14 r = -0.243 Degrees | Med wrist Pro/Supination 60 | Med knee Flex/Extension 44.9753 | Lumbar Flex/Extension 40.9082 | Lat elbow Pro/Supination 39.4216 | Med ankle Rotation 36.3352 |
| 15 r = -0.249 Degrees | Med ankle Rotation 60 | Lumbar Flex/Extension 48.4638 | Lat ankle Dorsi/Planta 39.2183 | Lat elbow Pro/Supination 38.1486 | Med knee Rotation 33.7687 |
| 16 r = -0.258 Degrees | Med ankle Rotation 60 | Med ankle Dorsi/Planta 50.9939 | Lat ankle Dorsi/Planta 41.2251 | Med ankle Ab/Adduction 37.5436 | Lumbar Flex/Extension 35.0978 |
| 17 r = -0.269 Degrees | Med ankle Rotation 60 | Med ankle Dorsi/Planta 45.5897 | Lat ankle Dorsi/Planta 43.8549 | Lumbar Flex/Extension 42.4098 | Med ankle Ab/Adduction 35.3605 |
| 18 r = -0.270 Degrees | Med ankle Rotation 60 | Med ankle Dorsi/Planta 41.0316 | Med knee Rotation 40.895 | Lumbar Flex/Extension 38.2871 | Lat ankle Dorsi/Planta 37.0919 |

Table 2: Descriptions of the ingress/egress constitutive shapes
Angles in shapes normalised to 60 degrees