Modelling the Car Seated Human Body using Composite Ellipsoidal Bodies and Evaluation of Size and Shape Specific Stiffness Data for Various Human Segments

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Abstract

Automobile is one of the primary modes of worldwide transport system, which must offer highest level of health, safety and comfort levels for the occupants inside. Health, safety and comfort of any moving vehicle and its human occupants are mainly characterized by the level of the vibration generated inside the human body. With the development of modern computer based technologies, over last few decades computerized simulations have been gaining huge importance to anticipate the level of vibration generated inside the automotive seated human body. Many simulation based research works had been conducted in past to predict the effect of vibration inside automotive-human assembly, though one of the key parameters to define the simulation set up, namely stiffness values of different human segments; had been collected from past relevant research studies or available testing data resources, which overlooked the real shapes and sizes of the human portions, hence, lacking the practical feasibility.

In this research paper, a simplified car seated human made of ellipsoidal segments has been proposed. The segmental dimensions and masses have been extracted from anthropometric database and later, the formulations for composite fibre-matrix configuration have been implemented. A systematic approach has been outlined to evaluate the three-dimensional stiffness values for all the human portions. The obtained stiffness values have been validated by comparing to the data obtained from similar kind of investigations and test results.

Keywords — *Ellipsoidal human segment, car seated human driver, three dimensional stiffness, computerized Simulation, human size specific stiffness.*

I. INTRODUCTION

As the modern technologies evolved, computer based simulation methods for monitoring, assessing and measuring the effects of vibration inside automotive seated human portions became popular in last few decades. Depending on the nature of study, either lumped mass parameter, multi-body or finite element method is used to judge the level of vibration in terms of frequency, acceleration or displacement. Each of the methods got its own pros and cons and numerous combinations of input factors, portions of interest and output results can be taken into account while carrying out an effective simulation methodology, however, one of the inevitable and common input parameters for the past explorations have been identified as stiffness values of human segments.

Automotive rear impact was analyzed using a bio-dynamic human model in MSC Visual Nastran 4D-2001 environment [1], where the seating postures were assigned based on a real life photograph of a car seated human body. The same study further explored the structure by assigning the contact mechanism between the automotive seat and human body by splitting the mating areas into rectangular or trapezoidal shapes, though was restricted to allow only a single frictional co-efficient value for all the portions. To, model the entire simulation with more reasonable frictional coefficients, the structure was taken to MATLAB environment, which was able to simulate the torso, back and buttocks of human body. The investigation recorded the simulation outputs at 50th ms, 89th ms, 100th ms, 150th ms, 200th ms, 250th ms and 300th ms. The entire course of analysis work used the stiffness values of human torso joints from BMH model and Bourdet-Willinger model. Bio-dynamic numerical algorithms were generated for the seated human body [2] under the effect of vertical vibration by considering four and seven degrees of freedom models and assuming hypothetical stiffness parameters from standard database. Research work on the vertical vibration [3] used the spring-dashpot system for vibration transmission and stated that the damping and stiffness values of the automotive seat cushion would be the major defining parameters for the vibration transmission from the automotive to human occupant.

Human muscle and seat foam properties were primary accounted during studies of experimental numerical interaction of human body and seat [4], stress generation inside muscles of seated human body [5], interaction of human tissues and automotive seat [6], three dimensional computerized programming of human buttocks ([7] and design of comfort parameters of automotive seat [8]. Modal analysis of the human portions in touch with automotive seat cushion using estimated stiffness values, was carried out [9] to extract first seven mode shapes under the frequency limit of 10 Hz. Human spine segments were made of rigid bodies, while the inter vertebral discs were constructed by deformable. An improved methodology was followed to design the articulated automotive seat by constructing several human bodies of different sizes [10]. The spine was modelled as deformable body, while ribs, skull and pelvis were considered as rigid bodies. Muscles and skins were incorporated to the entire assembly by assigning suitable tissue properties and the assemblies were taken to a new research facility [11] and configured to various postures to analyze the ergonomics of seated human occupant inside an automotive. Similar kinds of investigations were carried out using finite element [12], [13], [14], [15], [16], [3] to assess the human comfort inside automotive by taking into account the contact interactions between the automotive and human occupant. While exploring the effect of automotive seat orientation on the human body ergonomics [17], a comprehensive anthropometric data table had been estimated for comfortable seating position based on different genders and body sizes.

Acceleration transmission and sitting comfort of automobile seat were showed [18] using the contact between foam seat and human, while the pressure distribution inside the seat foam cushion was monitored [19] considering physical properties. Assessment of the human safety during the course of automotive collision [20] concluded that the automotive seat material properties along with the shape would be crucial factors for characterizing the human body dynamics in the side and rear directions.

From the previous research works on the automotive-human system, it is obviously clear that the investigations for vibration related assessments were made in different fields, though the assignment of stiffness parameters for the human segments were based on hypothetical or standard databases. Many of the past automotive-human studies focused on the hyper-elastic or viscoelastic material properties of the human tissue and ignored the size specific stiffness parameters.

During this research work, a non-robust car seated 50th percentile male human driver constructed by ellipsoidal solid bodies has been represented. The dimensions and masses of the ellipsoids have been gathered after careful consultation with worldwide anthropometric database. It has been assumed that the human bone-muscle structure is made of composite fibre-matrix material and the applicable formulations have been applied.

A step by step methodology has been drawn to calculate precise three-dimensional stiffness values for human head, chest, upper arm, lower arm, waist, thigh and leg. The acquired stiffness values have been authenticated by making a comparison with data used or found in similar relevant literatures.

II. METHODOLOGY

A. Masses of Human Portions

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A 50th percentile male body of 77.3 kg mass has been taken into account for carrying out this methodology. The human segmental masses have been calculated as a percentages of entire human body mass and for this purpose the databases and guidelines of the human portion [21], [22] have been consulted. Table I is showing the fractional figures of human segments with respect to entire human body.

TABLE I
Masses considered for male human segments in terms of percentages of total human body mass

Human portion	Mass of the portion (%)	Relevant database
Head	8.26	Plagenhoef et al., 1983
Whole trunk	55.1	
Thorax	20.1	
Abdomen	13.06	
Pelvis	13.66	
Total arm	5.7	
Upper arm	3.25	
Fore arm	1.87	
Hand	0.65	
Fore arm and hand	2.52	
Total leg	16.68	
Thigh	10.5	
Leg	4.75	
Foot	1.43	
Leg and foot	6.18	
Head and neck	6.94	Leva, 1996
Trunk	43.46	

Human portion	Mass of the portion (%)	Relevant database
Upper arm	2.71	
Fore arm	1.62	
Hand	0.61	
Thigh	14.16	
Shank	4.33	
Foot	1.37	

B. Dimensions of Human Portions

Human dimensions measurement guidelines have been provided in the international standards PD ISO/TR 7250-2:2010 and BS EN ISO 7250:1998. Anthropometric dimensions of human bodies have been outlined [23] based on analysis and factors for human comfort have been shown in the handbook on the human ergonomics [24]. Biodynamic anthropometric data for different countries have been published in industrial personnel in Asia [25], elderly Chinese people [26], Turkish females [27], Mexian adult people [28], rugby athletics [29] and Italian gymnasts [30].

After thorough consultation with all the relevant guidelines, standards, literatures and handbooks, the dimensions of all the segments of a 50^{th} percentile 77.3 kg male human have been collected and presented in Table II.

TABLE II
Collected human segmental dimensions

Dimension for various human portion	Dimension (cm)
Standing Height	175.49
Shoulder Height	59.80
Head Length (Including Neck)	31.31
Head Breadth (Including Neck)	15.50
Shoulder to Elbow Length	36.88
Forearm Hand Length	26.92
Biceps Circumference	24.40
Elbow Circumference	27.30
Forearm Circumference	22.80
Wrist Circumference	15.60
Thigh Circumference	46.70
Upper Leg Circumference	42.40
Knee Circumference	35.10
Calf Circumference	31.90
Ankle Circumference	23.90
Foot Breadth	10.00
Foot Length	26.50

Dimension for various human portion	Dimension (cm)
Upper Leg Length	60.50
Thigh Thickness	15.50
Lower Leg Length	45.00
Chest Depth	24.50
Abdominal Depth	27.50
Average Torso Depth	26.00
Torso Height	59.80
Torso Top	48.50
Torso Bottom	39.00
Average Torso Width	43.75
Hand Length (Fist)	6.94
Hand Width	9.03
Hand Depth	2.41
Upper Leg Length	61.54
Lower Leg Length	50.39

C. Human portions Represented by Ellipsoidal Bodies

Robust human portions can be represented by simplified ellipsoidal bodies. This method is advantageous to define the three dimensional stiffness values of human portions along the principal axes of ellipsoids as functions of directional lengths and valid for various ranges of human shapes and sizes.

Study in academic environment on the eigen vectors of human segments modelled the human bodies with truncated ellipsoids [31] and dimensions of each segment had been taken from anthropometric database. Investigation on human arm and leg [32] outlined the idea of presenting human segments through ellipsoidal cross-sectional areas.

The displacement magnitude of a particular point on an ellipsoidal cross-section has been displayed in Fig 1 and the hypothetical formulation for calculating the displacement is shown in Equation (1).

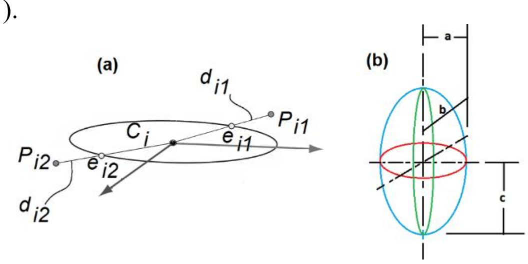

Fig 1: (a) Displacement of a point on ellipsoidal cross-section and (b) axial directions considered

$$D(u_{ij}, v_i) = d_{ij} = \|P_{ij} - e_{ij}\| \quad (1)$$

$i = 1,.....M,$

$j = 1,.....N_i$

$(u_{ij}, v_i) =$ Surface parameters of the point e_{ij} on ellipsoid surface C_i.

In the methodology in this paper, the human body has been assumed to be made of head, neck, legs, thighs, feet, upper arms, lower arms, hands and torso. From the comprehensive anthropometric data in Section II.B, the dimensions of ellipsoidal portions have been derived as shown in Table III.

TABLE III
Dimensions of ellipsoidal segments

Body Segment	Ellipsoid Parameter (cm)		
	a	b (depth)	c
Head including Neck	7.75	7.75	15.66
Torso	21.88	13.00	29.90
Upper Arm	3.88	3.88	18.44
Lower Arm	3.63	3.63	13.46
Hand	4.52	1.21	3.47
Thigh	6.75	7.75	30.25
Leg	5.08	5.08	22.50
Foot	5.00	3.05	13.25

D. Posture of Car Seated Male Human Body

The comfortable sitting posture of car seat human can be configured based on the international standards ISO/TC 159/SC 1, ISO/TC 159/SC 3 and ISO/TC 159/SC 4 for principles of ergonomic, anthropometric data and bio-mechanical interaction between system and human, respectively. To make this approach more practical, all the angular dimensions of a car seated human body have been measured from a photograph of car seated human driver of 77 kg mass.

The photograph has been imported into Solidworks 2016 drafting environment to measure all the angular orientations in three dimensional space and from those measured values, a parametric seated human driver model has been established in Solidworks 2016. The imported photograph and developed 3D model are shown in Fig 2.

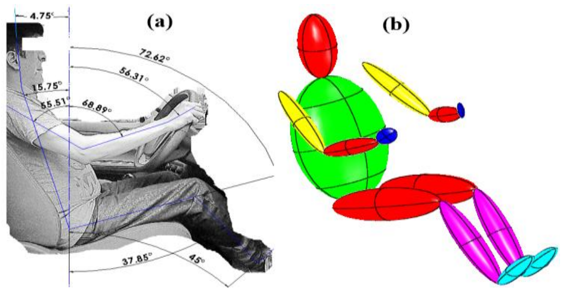

Fig 2: (a)Real human male driver of 77 kg mass and (b) CAD model of driver

E. Young's Moduli of Human Body Segments

Precise value of Young's Modulus (YM) for combined human bone and muscle structure is a tough challenge as the bone, muscle and soft tissue are mechanically non-linear and exhibit hyper-elastic and viscoelastic material properties. Exploration of human bone properties with respect to variable age and gender [33] found the YM value of bone as 20.04 GPa., while similar sort of finite element simulation [34] considered the YM of bone as 15 GPa. Indentation testing and measurement of tensile strength of biological tissue concluded that the YM values for muscles and tissues would be in-between 3 kPa and 8 kPa. In this research methodology, YM values for human muscles and bones have been considered as 8 kPa and 20.04 GPa, respectively.

Depending on the nature of the bio-dynamic study, human bone-tissue structure can be modelled using the formulations of fibre, composite or silicon material. Stiffness parameters for the composite materials can be calculated using fibre-matrix equations, hence, usage of composite materials is advantageous compared to other materials. The bone-muscle structure during this research procedure has been assumed to me made of composite material. For the ellipsoidal human segments, the fractions of muscles and bone have been taken as 85% and 15%, respectively as per the guideline provided in advanced nutrition database [35]. A simplified fibre-matrix composite assembly for human segment is shown in Fig 3 and three directional YM values for human segments have been obtained using the co-relation in Equation (2) and Equation (3).

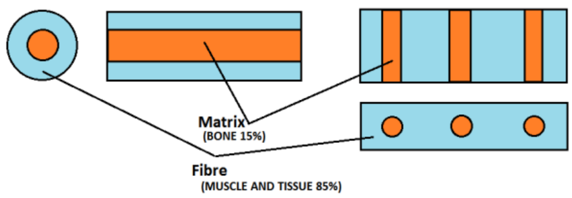

Fig 3: Matrix -fibre arrangement representing human bone, muscle and tissue

$$E_{i-Axial} = E_{Muscle} \times f_{Muscle} + E_{Bone} \times (1 - f_{Muscle})$$
(2)

$$E_{i-Transverse} = \frac{E_{Muscle} \times E_{Bone}}{E_{Muscle} \times (1 - f_{Muscle}) + E_{Bone} \times f_{Muscle}}$$
(3)

$E_{i-Axial}$ = Axial YM of ith segment

$E_{i-Transverse}$ = Transverse YM of ith segment

The evaluated for axial and transverse YM values are 3.006 GPa and 9.412 KPa, respectively.

III. RESULTS: THREE-DIMENSIONAL STIFFNESS VALUES FOR HUMAN PORTIONS

Combining the dimensions from Section C and YM values from E, three directional stiffness parameters for the human segments have been calculated using theoretical relationship between stress, strain, force and cross-sectional area as shown in Equation (4).

$$K_{ij-Directiond} = \pi \frac{E_{ij-Directiond}\, a_{per-ij-Directiond}\, b_{per-ij-Directiond}}{C_{ij-Directiond}} \quad (4)$$

$K_{ij-Directiond}$=Stiffness of j^{th} segment in i^{th} direction

$E_{ij-Directiond}$=YM of j^{th} segment in i^{th} direction

$a_{per-ij-Directiond}$=Half axis (Transverse axis-1) length of the of j^{th} segment perpendicular to i^{th} direction

$b_{per-ij-Directiond}$=Half axis (Transverse axis-2) length of the of j^{th} segment perpendicular to i^{th} direction

$C_{ij-Directiond}$=Half axis length of the of j^{th} segment in i^{th} direction

The obtained stiffness values for the human portions are summarized in Table IV.

TABLE IV
Axial and lateral stiffness values of human segments

Body Segment	Axial Stiffness (kN/m) - C Axis	Lateral Stiffness (kN/m) - B Axis Depth	Lateral Stiffness (kN/m) - A Axis
Head including Neck	362249.86	4.63	4.63
Torso	898003.69	14.87	5.25
Upper Arm	77246.85	5.45	5.45
Lower Arm	92403.13	3.98	3.98
Hand	148038.00	3.84	0.27
Thigh	163268.40	7.79	10.27
Leg	108208.38	6.65	6.65
Foot	108670.55	6.42	2.39

IV. VALIDATION AND DISCUSSION

The top and bottom limits of axial stiffness parameters are obtained as 898003.69 kN/m for torso and 77246.85 kN/m for upper arm, respectively, while the highest and lowest magnitudes in lateral directions are found as 14.87 kN/m at torso and 0.27 kN/m at hand, respectively. To validate the stiffness values obtained, past references in relevant fields have been explored.

Human body in seated posture were modelled using truncated ellipsoids [31] and 15 degrees of freedom system. Maximum and minimum axial stiffness limits were found to be 3119.12 kN/m at thigh and 75.61 kN/m at hand, respectively, while maximum and minimum lateral stiffness limits were found to be 2642.92 kN/m at central torso and 129.24 kN/m at foot, respectively. Investigation on the human leg [36] assumed the stiffness value as 28.5 kN/m. Research work on dynamic impact on human soft tissue [37] tried to estimate the stiffness constant for human tissue using 27 number of trials. The range of stiffness values were found to be n-between 8.832 kN/m and 31.779 kN/m. Human body had been modelled using mass-spring-damper [38] and stiffness matrices had been generated in multi-body environment. The results showed that the stiffness constants for various human segments were appearing in-the range of 0.05 kN/m and 100000 kN/m.

Human bone and muscle structure is a very complex assembly where numerous factors are associated and any one of these factors on its own can be responsible for altering the stiffness behaviour of the structure. Distribution of tissues over the bone, homogeneousness of bone and soft tissue, expansion or contract condition at the time of stiffness measurement, age of the human taken into account, shape and size of human portion, variation in human structure depending on different geographical area etc. all play major roles in defining the stiffness constant of human body segments. Hence, it is inevitable to have mismatches in stiffness values for same human components obtained from different sources.

The range of stiffness constant values received from the results of this research work, are falling within the range described in past studies and literatures. From the discussion in this section, it can be concluded that this simplified methodology can successfully be implemented for predicting the stiffness values of car seated human portions.

V. CONCLUSIONS AND SCOPES OF FURTHER DEVELOPMENT

In this research paper, a unique and simple technique has been proposed to forecast the stiffness parameters inside car seated human body portions. From the results of this analysis work, the following conclusions can be drawn:

A. This methodology can be implemented efficiently to any portion of the human body to predict the three-dimensional stiffness constants. In this paper, this methodology has been executed on human driver inside a car, though ideally this stiffness measurement procedure can fruitfully be applied to the any industrial or academic sector demanding the anticipation of stiffness data for human parts.

B. Human portions can be modelled by ellipsoidal bodies in three dimensional special plane as per the dimensions provided in anthropometric guidelines and bone-muscle arrangement can be represented through composite based matrix-fibre system to evaluate human shape and size dependent stiffness data. The stiffness values obtained from this technique, will have a higher degree of feasibility than those of collected from theoretical database or standards.

C. This procedure is able to estimate the stiffness data inside human segments in a moderately reasonable way and results from this method are in agreement with defined or assigned stiffness values in other relevant literatures.

Enormous scopes of further improvement are there to take this emerging methodology to advanced level. Firstly, splitting the ellipsoidal human segments into more number of mini-ellipsoidal elements would be beneficial for more accurate results. This process will be time consuming because of the requirement of an anatomically correct human body besides gathering data from anthropometric manuals. But, colleting dimensions for mini-ellipsoids will enhance the accuracy of the results to a great extent. Secondly, further research exploration to find ways to assign more number of input parameters as explained in Section 0, will be advantageous. With the increment of number of key input parameters, the chances of obtaining more improved results will be increased. Thirdly, taking into account the operating environmental scenario and its impact on the human portions, will obviously be useful. Considerations of forces exerted to human parts from operating condition e.g. load from steering wheel to hand, pressure from break or clutch on the leg, contact pressure from seat to pelvis etc., will certainly add value to results.

Based on the discussions on results, validation, conclusion and scope of improvement, statement can be made that this technique is providing realistic outputs on stiffness data, which can be effectively used in vibration related bio-dynamic problems. Fine tunings and additions of input parameters can lead this methodology to anticipate stiffness data inside human portions in more convincing way.

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