On scaling of human body models

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Abstract

Human body is not an unique being, everyone is another from the point of view of anthropometry and mechanical characteristics which means that division of the human body population to categories like 5%-tile, 50%-tile and 95%-tile from the application point of view is not enough. On the other hand, the development of a particular human body model for all of us is not possible. That is why scaling and morphing algorithms has started to be developed. The current work describes the development of a tool for scaling of the human models. The idea is to have one (or couple of) standard model(s) as a base and to create other models based on these basic models. One has to choose adequate anthropometrical and biomechanical parameters that describe given group of humans to be scaled and morphed among.

1. Introduction

This article describes a deep review on morphing and scaling basics and methods developed to generate models representing subjects of varying anthropometry and of search of anthropometric data. Chosen methods and data are then applied to human body models used in crash tests.

The philosophy of a scaling algorithm is simple: a reference human body can be scaled into any desired target body. As the philosophy is simple, the concrete interpretation is not simple at all. We have to take into account gender, race, geographical conditions of living, body training and other factors that influence the proportions and mechanical characteristics of the human body. We should also distinguish between scaling and morphing. Let us call scaling the global change of major human body parts dimensions whilst morphing considers more details (e.g. female breasts etc.). This article considers scaling method.

2. Human Variations

This section is taken from [15] by S. Molnar. There is no doubt about human biological diversity. Human body size varies widely – from 1.4 m tall pygmies in Africa and Oceania to the 2 m tall Nilotic peoples of East Africa. Europeans themselves vary from short (in southern Europe) to tall (in northwestern Europe). Body shape ranges from a thin and linear built to a

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shorter and heavier one, as seen in the contrast between several arctic people and native Australians. Face form and head shape are other distinguishing characteristics that may differentiate between populations. All of these features have misled writers to draw conclusions about the relationship between groups.

Biological variability today appears to result from the combined influence of human behaviour and natural forces that have been at work throughout human prehistory. The size of populations, their isolation, and their adaptation to environmental stresses contribute to or detract from the survival of individuals or of the entire group. Each population grouping also reflects, to some degree, the experiences of its ancestors and gives evidence of elements in its environment that have been shaping it through time. This modification over the course of generations is still proceeding and may contribute to future population diversity. No matter how we may define of classify clusters of populations today, their composition will undoubtedly change over future generations as a result of major alternations in evolutionary forces through human adaptation and because of continuing migrations and interbreeding.

During the nineteenth century, numerous attempts were made to introduce scientific method into the analysis of measures of human diversity. Statistical methods were applied to the interpretation of variation in size, and the concept "average man" was introduced as a "scientific" way of establishing types. Such "ideal types" or averages work well for sorting out widely differenting species, but matters become more difficult when investigators are dealing with closely related organisms, and "type" becomes a mere abstraction for comparisons of subspecies (or races). This difficulty increases when we search for forms that match notions of the ideal specimen, a factor that has caused many problems in studies of human evolution.

Throughout the development of anthropometry there has been the belief that if only enough measurements were taken, facts would emerge that would clear up the mystery surrounding human origins and variations. Numerous select groups were measured throughout Europe. Given the vast number of measurements made during the course of anthropometric studies, a means of analysis had to be devised, and several mathematicians developed statistical methods. Foremost among these early statisticians was Lambert Quetelt (1796 – 1874), an astronomer and mathematician interested in social statistics. He gathered anthropometric measurements from a large number of military conscripts, university students, and prison convicts, and comparisons were made with a broader sample of European populations. Statistically significant differences of height, weight, and several body proportions were reported between samples – differences that were attributed to environment or heredity [15].

Body Size. The height of normal adults in our species ranges around $1.4\ m$ well over $2\ m$. These limits are exceeded occasionally but seem to represent a norm for modern stature. The variation in human stature is distributed among the world's peoples in some very interesting ways. Though there appears to be a tendency toward taller people farther from the equator (as in northwestern Europe) and shorter people nearer the equator, numerous exceptions exist [15].

Body Form. A relative simple way of determining body proportion is to compare a person's standing height and sitting height. The *cormic index*[1] or ratio between the two measurements indicates proportion of stature owing to the legs or the trunk. For example, in populations with relatively short torsos and long legs (such as the Australian Aborigines and many Africans) the

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[1]Proportions of body length are easily measured by dividing sitting height by standing height. This gives an index that describes the contribution of the head and trunk length to total body height.

cormic index is less than 50 (a ratio of 50 would indicate the legs and trunk plus head were approximately the same length). The tall stature of Nilotic groups in East Africa north of Lake Victoria is due more to their very long legs than to trunk length, whereas most descriptions of the Pygmies note their elongated trunks and short legs and long arms [15].
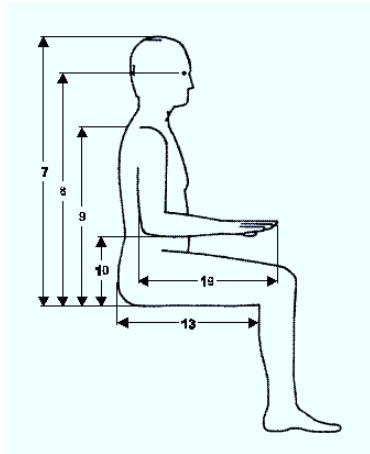

Fig. 1. Definitions of the dimensions measured on the eldery population sample. *7 – sitting height, 8 – sitting eye height, 9 – sitting shoulder height, 10 – sitting elbow height, 13 – buttock–popliteal length, 19 – elbow–fingertip length* [10].
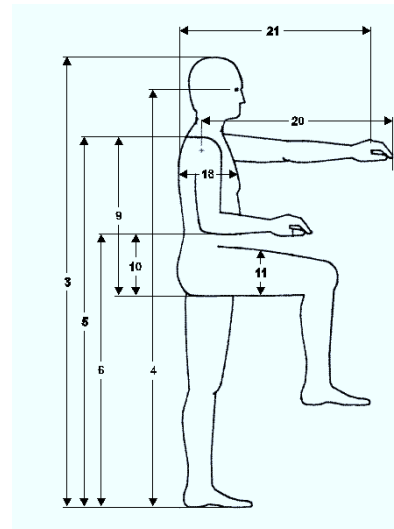
Fig. 2. Definitions of the dimensions measured on the eldery population sample. *3 – stature, 4 – eye height, 5 – shoulder height, 6 – elbow height, 9 – sitting shoulder height, 10 – sitting elbow height, 11 – thigh thickness, 18 – chest depth, 20 – upper limb length, 21 – shoulder grip length* [10].

Body Weight. Weight also varies over a wide range, but it does not correlate closely with stature. Some tall people are light in weight compared with heavier shorter people. Adult weight changes from about 30 kg to more than 100 kg depending on diet and, perhaps, on genetic factors as well. There seems to be little ethnic variation in body weight or in response to a surplus dietary intake, though many groups of Native Americans, Pacific Islanders, and Australian Aborigines become extremely obese when they change to the refined high–carbohydrate, high–fat diets typical of American diets today. Usually, the excess weight is stored as layers of fat just below the skin, distributed over the body but more concentrated over abdomen. However, there are examples of some differences. Khoi and San or !Kung women of South Africa, when well fed, develop especially large buttocks, which are expanded by an enlargement of fat cells that are supported by bands of fibrous tissue. This may be an adaptation to high environmental temperatures, because the concentration of fat more in one ragion would increase the body's ability to dissipate metabolic heat through the skin's surface. The fat layer, if evenly distributed over most of the body, acts as insulation and would reduce the dissipation of body heat transfer through radiation. Though dietary quantity and quality affect bodily proportions and weight, there is a close correlation with mean annual temperature. Generally, in colder climates people are much heavier for their height than people in warmer regions, and the ratio between height and weight of the individuals may be even more significant than limb ratios or trunk limb proportions.

3. Anthropometric Data

In [6], the authors discuss a method which they developed and applied to crash–dummy models. In their study, different scaling factors are specified for x, y, and z dimensions. Furthermore different scaling factors are applied for different body parts. Thus the model geometry can be adapted freely to the desired anthropometry parameters. Input for the scaling is a set of target anthropometry parameters (see Table 1). The corresponding parameters have also been evaluated for the standard models which are to be scaled.

weight	standing height	seated height
head length	head breadth	head to chin height
neck circumference	shoulder breadth	chest depth
chest breadth	waist depth	buttock depth
hip breadth, standing	shoulder to elbow length	forearm–hand length
knee height, seated	ankle height, outside	foot breath

Tab. 1. Anthropometry parameters [6].

Initial scaling factors are simply derived as the ratio of target length divided by standard length. The resulting scaling factors are then applied to the standard model. Finally the mass and the main dimensions of the resulting model are checked. The mass is only an indirect result of the scaling process and therefore normally deviates slightly from the specifications. Therefore a second phase of the scaling, the so called correction is performed. The model is simulated repeatedly to optimise the prediction of mass, erect standing height, seated heigth and shoulder width. In this correction phase only the geometry scaling factors are optimised. No variation of the assumed body tissue density is performed. In addition to the geometry, all other model parameters were scaled (geometry, mass and moments of inertia, all joint characteristics, contact characteristics, forces, . . .).
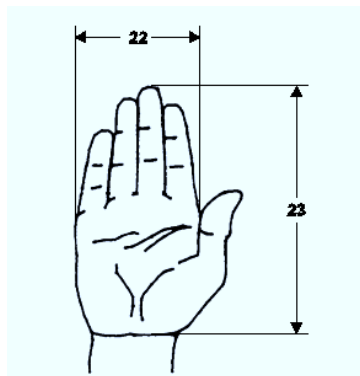

Fig. 3. Dimensions measured on eldery population sample. *22 – hand length, 23 – hand breadth* [10].

Happee et al. note in [6] that scaling is performed assuming that all material properties are invariant with subject size. Biomechanically this seems to be an acceptable approach for adult subjects. For scaling towards children, or to simulate eldery persons the variation of material properties should be included. The assumption of equal density leads to analytical scaling rules for mass, centre of gravity and rotational inertia. For the scaling of stiffness and damping the assumption of identical material parameters leads to simple scaling rules. For instance when

scaling the force deflection behaviour of an ellipsoid, deflection scales with the representative length and force scales with surface and thereby with length to the second power.

Kothiyal and Tettey [10] present anthropometric data on eldery people in Australia. Data were collected in the metropolitan city of Sydney, NSW, Australia. In all 171 eldery people (males and females, aged 65 years and above) took part in the study. Mean values, standard deviations, medians, range, and coefficients of variation for the various body dimensions were estimated.

Figures 1 – 3 show definitions of the dimensions measured on the eldery population sample by Kothiyal and Tettey. [10].

Similar paper by Prado-León et al. [18] deals with anthropometric study of Mexical primary school children age 6 – 11 years in the metropolitan area of the city of Guadalajara. A set of 50 body dimensions was taken based on international standards. The sample consisted of 4758 children (boys and girls). Children were divided into age groups according to the grade of each child at the moment of the survey. The school's samples were selected randomly from the four sections in which the city is devided. Within each school selected, children were chosen randomly. Subjects wore light shortpants and T shirts only, and were barefooted. Figures 4 – 6 show definitions of the dimensions measured on the children population. Mean values and standard deviations were determined for each age group of children.
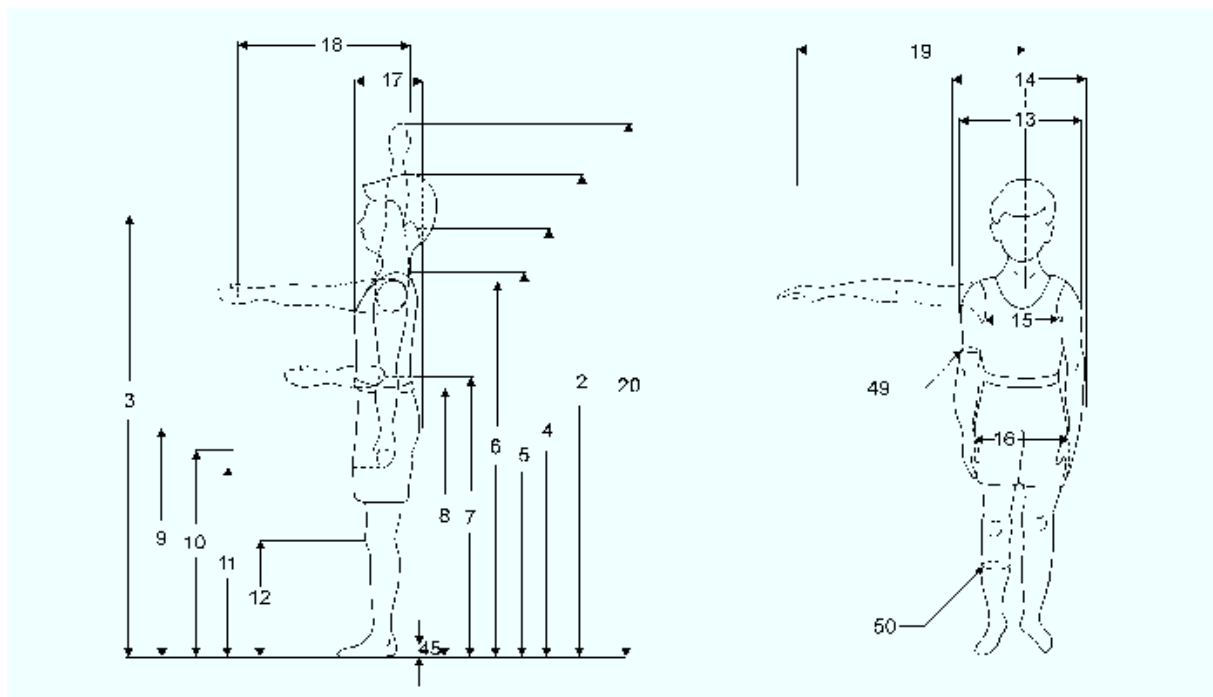

Fig. 4. Anthropometric measurements of standing posture [18].

Liu et al. studied in [11] the anthropometric dimensions of female maquiladora workers. 12 body dimensions were measured using traditional 3D methods. 110 female operators in maquiladora plant were randomly selected to participate in the survey. Following statistical characteristics were obtained for each measured body dimension: mean, standard error, standard deviation, coefficient of variation, minimum, maximum, 5th, 50th, 95th percentile, etc. Correlation between anthropometric parameters was also studied.

Mououdi in [16] presented the anthropometric characteristics of Tehran University students age 20 – 30. 179 students were randomly chosen and 28 body dimensions were measured.

In similar paper Mououdi and Choobineh [17] presented the anthropometric characteristics of students age range 6 – 11. 17 body dimensions were measure. In both papers, means, standard errors, standard deviations, and other statistical moments and characteristics were calculated.

Anthropometric data of eldery women in Poland were studied by Jarosz [8]. The results of the measurements of 33 anthropometric characteristics of 106 women aged 60 and above are presented and discussed. Means, standard deviations and 5th and 95th percentiles were calculated. Standard measurement technique was used in this study.

Seitz et al. [21] deals with anthropometry and measurements of posture and motion. The measuring system presented in this study is based on a simple projection procedure. The subject is photografied from different angles with several cameras. A PC is then used to compute spatial points from the pictures three–dimensionally.
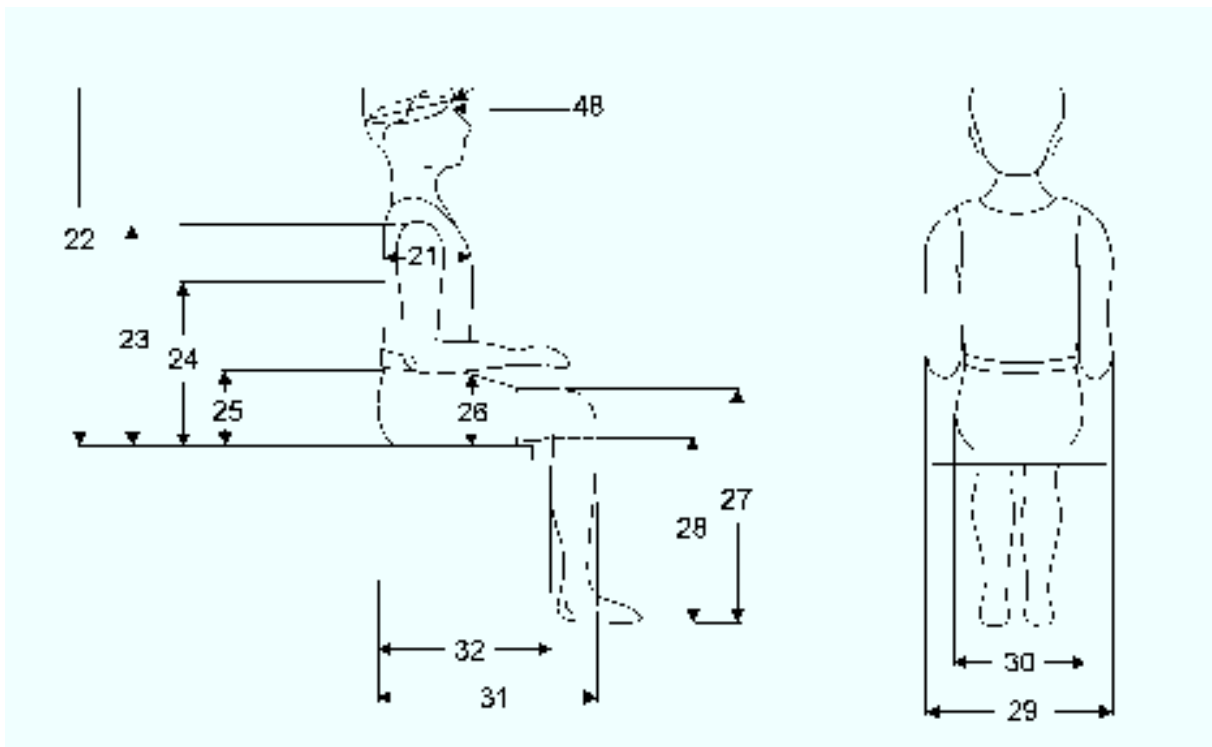

Fig. 5. Anthropometric measurements of sitting posture [18].
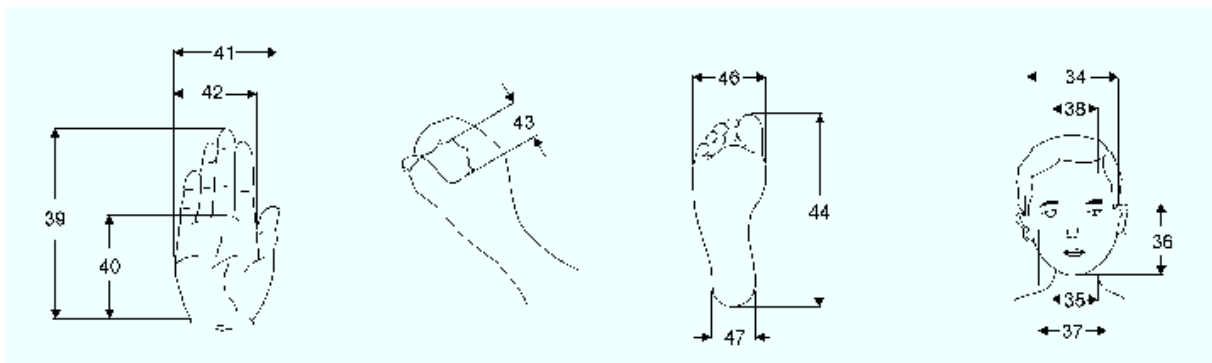

Fig. 6. Anthropometric measurements of face, hand and foot [18].

Mamansari and Salokhe investigated in [12] the static strength and physical work capacity of ten male and ten female labourers randomly selected. The anthropometry of these subjects was determined by taking 42 body dimensions and body weight and lung capacity.

Botha and Bridger [5] studied the anthropometry and anthropometric fit of a group of nurses in Western Cape private hospitals. 27 anthropometric variables were measured using a sample of 100 nurses. The results are discussed respecting the questionnaire findings concerning with numerous problems in the work environment and musculoskeletal pain.

Bolstad et al. presented in [4] an anthropometry study of Norwegian light industry and office workers. 200 males and 199 females employees of light industry and office work, between 20 and 39 years of age were studied. Body mass plus 29 different body dimensions were measured. Means and standard deviations were calculated as well as 1st, 5th, 50th, 95th and 99th percentiles.

An anthropometry study of Algerian date–palm farmers was carried out by Mokdad in [14]. 36 body dimensions were measured. Means, deviations, percentiles and correlation coefficients between body dimensions were calculated.

The aim of study [20] by Schibye et al was to investigate the effect of waste collection on the physical capacity of the workers. A total of 19 young and 28 eldery male waste collectors and two age–matched control groups participated. The aerobic power was estimated. The maximal isometric muscle strength was measured for back extension and flexion, shoulder elevation and abduction, and handgrip.

Detailed measurement of head proportions was performed by Meunier et al., [13]. This paper deals with helmet accomodation analysis using 3D laser scanning.

A lot of useful anthropometric data serving as input data for scaling and morphing could be found in articles presented in the *Journal of Applied Ergonomics* or in the *International Journal of Industrial Ergonomics*.

Summarizing the review for the scaling of the human models, we need:

- To choose a set of the anthropometric parameters (body dimensions) important for our study.

- To define target groups of people to whom the study might be intended.

- To find proper anthropometric data characterizing chosen target groups as the functions of a parameter (age and gender) of each group.

- To develop appropriate algorithms and methods scaling anthropometric data according to a parameter (age and gender) within each target group.

Those objectives are considered to be the most important at the beginning of the scaling procedure. Defining target groups of people is of crucial importance. Anhtropometric parameters should be chosen according to segments of the human body model.

4. Data and method

The target group is a set of 5000 Czech sportsmen (males and females) measured by the Charles University in Prague (Faculty of Sciences, Department of Anthropology and Human Genetics) during the Czechoslovak spartakiade in 1985 [3]. Such specimen is very unique from the statistical point of view. Based on the experimental data covering a wide population and the

reference human body models, we are able to generate a male or a female of age from 6 years old children till 55 years old adults.

Especially for children, the body proportions are not uniquely scalable from any adult and morphing is needed. That is why only older children and adults has useful shape of the body. Further morphing will serve this problem.

For the scaling algorithm, reference human articulated rigid body (HARB) models are chosen. They are the 50%-tile ROBBY2 male human articulated rigid body model and the 5%-tile ROBINA female human articulated rigid body model [2, 7]. These models have already been developed for a long time in collaboration between University of West Bohemia in Plzeň, Czech Republic and ESI Software in Paris, France. The structure of the models is based on [19] where the segmentation of the body is done very similarly according to the list in the previous paragraph. Hence, the ROBBY and ROBINA human articulated rigid body models are already segmented in the same structure where the segments are implemented as rigid bodies connected by joints. By the development, there are more segments and more joints than in the basic list above, e.g. the spinal column is separated by adding one rigid body per each particular vertebrae, however, for the purpose of scaling, we can tie several rigid bodies belonging to a segment together and scale them together as one segment because the scaling influences just the geometry, i.e. coordinates of the nodes, and no other entity of the model. This access can be also applied for scaling of inner organs if they are implemented inside the model. Hence simplified scaling can be done on deformable models as well when they are divided into segments.

Based on the above-mentioned segmentation, all major dimensions of particular segments measured [3] are scaled as a function of gender and age. For a chosen age, we provide an interpolated average anthropometric dimensions based on data [3]. By scaling, the anthropometric dimensions of particular segments are used to scale the segments of reference human body models in a local coordinate system. There is an advantage using local coordinate system that the model can be pre-positioned, e.g. in the sitting position, and it is not necessary to stand him/her for the scaling and sit him/her back after the scaling. For standing model with arms along the body, the local coordinate systems are parallel to the global coordinate system.

Concerning the deformable models, the dynamical characteristics are changed by changing the geometry since the density distribution. For the rigid body based model, the algorithms scales the dynamical characteristics (masses and inertias) for the rigid bodies as well. The response of joints is not considered for scaling at now.

5. Scaling algorithm

The reference model is composed of rigid bodies connected by joints. Each rigid body is defined via geometrical surface, e.g. nodes defining the position. Each joint connecting 2 rigid bodies is defined via 2 nodes, each belonging to one rigid body. These 2 nodes create a joint element. Simply saying, the scaling algorithm is nothing else than scaling the nodes and re-position all scaled rigid bodies in order to be connected in the same way as before scaling. In the reference model, there are more rigid bodies than major anthropometric segments and hence, some rigid bodies form a single segment for scaling [2, 7].

For the reference model, the nodes corresponding to the anthropometrical points defined above have been marked. Based on these nodes, the scaling has been done. Supposing our reference models, the scaling algorithm can be divided into following steps:
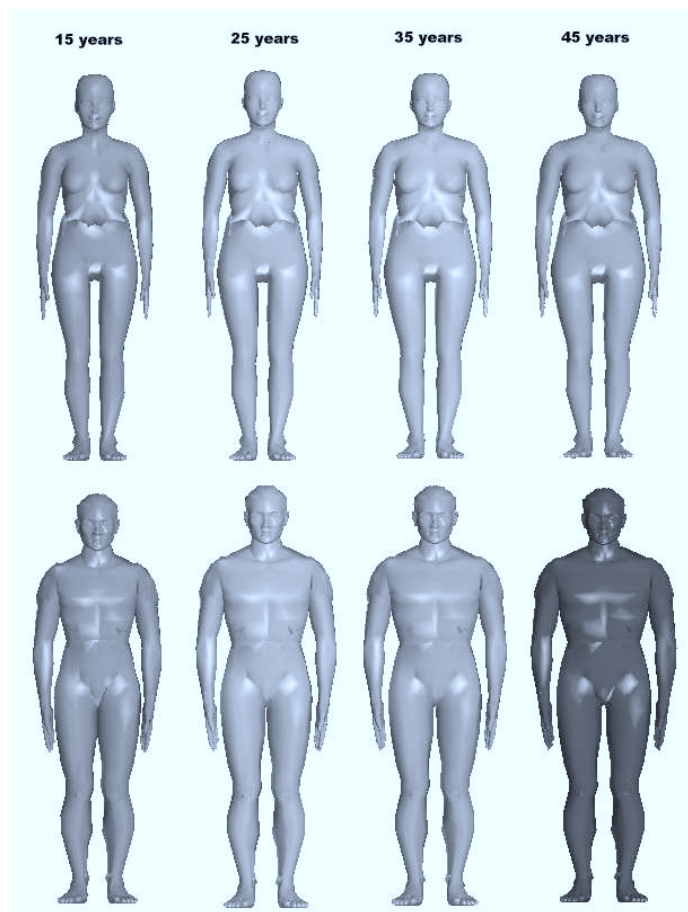
Fig. 7. Age dependent ROBINA (upper) and ROBBY2 (lower) models.

1. **Scaling all segments with respect to local coordinate systems.** For particular segment, each node of the segment is moved and rotated from the local to the global coordinate system firstly (in order the local coordinate system is in the same position as the global one). Then, the node is scaled in all three directions and rotated and moved back to the local coordinate system.

2. **Update of inertia matrix.** The dynamical characteristics of each rigid body (mass and moments of inertia) are re-computed based on the scaling procedure changing the shape.

3. **Connecting the model back together in order to have original joint nodes distances.** Using the tree definition of the segments, all segments are reconnected back in order the joints defined have the same initial offset as before scaling (two nodes of a kinematic joint should have the same distance in all three global directions as before scaling).

4. **Move the H-point to original coordinates.** The whole structure is moved in order the H-point's coordinates are the same as before scaling. H-point is in the middle between the hip joints and the reference model.

We can write the basic mathematical operations used in the above-mentioned algorithm as

follows. Defining vector

$$\boldsymbol{x} = \begin{bmatrix} x \\ y \\ z \end{bmatrix},\qquad(1)$$

where x, y and z are coordinate in the 3D coordinate system, each segment is moved in order the origins of local and global coordinate systems are equal as

$$\boldsymbol{x}^{moved} = \boldsymbol{x}_{local} - \boldsymbol{x}_0,\qquad(2)$$

where subscript $_{local}$ means local coordinate system and subscript $_0$ means global origin. Then, the node is rotated to the global coordinate system as

$$\boldsymbol{x}_{global} = \boldsymbol{R}^T \boldsymbol{x}^{moved},\qquad(3)$$

where

$$\boldsymbol{R} = \begin{bmatrix} \mathbf{i}_{local}\mathbf{i}_{global} & \mathbf{j}_{local}\mathbf{i}_{global} & \mathbf{k}_{local}\mathbf{i}_{global} \\ \mathbf{i}_{local}\mathbf{j}_{global} & \mathbf{j}_{local}\mathbf{j}_{global} & \mathbf{k}_{local}\mathbf{j}_{global} \\ \mathbf{i}_{local}\mathbf{k}_{global} & \mathbf{j}_{local}\mathbf{k}_{global} & \mathbf{k}_{local}\mathbf{k}_{global} \end{bmatrix}\qquad(4)$$

is the rotation matrix from the global to the local coordinate system. i, j and k are the unit vectors of local coordinate systems. Now, the scaling is proceed as

$$\boldsymbol{x}_{global_{scaled}} = \begin{bmatrix} k_1 & 0 & 0 \\ 0 & k_2 & 0 \\ 0 & 0 & k_3 \end{bmatrix} \boldsymbol{x}_{global},\qquad(5)$$

where k_i, $i \in \{1, 2, 3\}$ are the scaling factors in the local scaling coordinate system. Now we must rotate it back to the local coordinate system as

$$\boldsymbol{x}_{local_{scaled}}^{moved} = \boldsymbol{R}^T \boldsymbol{x}_{global_{scaled}}.\qquad(6)$$

Moving back to the local coordinate system, we have

$$\boldsymbol{x}_{local_{scaled}} = \boldsymbol{x}_{local_{scaled}}^{moved} + \boldsymbol{x}_0.\qquad(7)$$

Putting equations (3), (4), (6) and (7) together, we get

$$\boldsymbol{x}_{scaled} = \boldsymbol{x}_0 + \boldsymbol{R} \begin{bmatrix} k_1 & 0 & 0 \\ 0 & k_2 & 0 \\ 0 & 0 & k_3 \end{bmatrix} \boldsymbol{R}^T (\boldsymbol{x} - \boldsymbol{x}_0).\qquad(8)$$

After scaling all segments, it is necessary to re-connect them in order the joints are in the original position. The basic location of the whole model in space is done by the H-point. So firstly, the segment accommodating the age point is moved in order the H-point to be in the original position. Then, by the definiton of the open tree structure, we move following segments from the segment accommodating H-point in order to have the original joint geometry kept. Here the necessity of an open tree is shown. However, if we want to scale a model having closed tree inside, we can open it by releasing the joint closing a tree and modify the geometry after scaling manually.

Let us suppose the scaling factors in the 3 coordinate system axes as k_1, k_2 and k_3. Having segment mass m and ineria matrix

$$\boldsymbol{D} = \begin{bmatrix} I_x & -D_{xy} & -D_{xz} \\ -D_{xy} & I_y & -D_{yz} \\ -D_{xz} & -D_{yz} & I_z \end{bmatrix}, \tag{9}$$

the new inertial characteristics dennoted by left upper index ^{S} can be written in form

$$^S m = k_1 k_2 k_3 m, \tag{10}$$

$$^S I_x = k_2 k_2 k_2 k_1 k_3 N_y + k_3 k_3 k_3 k_1 k_2 N_z \tag{11}$$
$$^S I_y = k_1 k_1 k_1 k_2 k_3 N_x + k_3 k_3 k_3 k_1 k_2 N_z \tag{12}$$
$$^S I_z = k_1 k_1 k_1 k_2 k_3 N_x + k_2 k_2 k_2 k_1 k_2 N_y \tag{13}$$

and
$$^S D_{xy} = k_1 k_1 k_2 k_2 D_{xy}, \quad ^S D_{xz} = k_1 k_1 k_3 k_3 D_{xz}, \quad ^S D_{yz} = k_2 k_2 k_3 k_3 D_{xz}, \tag{14}$$

where

$$N_x = \frac{1}{2}(-I_x + I_y + I_z), \quad N_y = \frac{1}{2}(I_x - I_y + I_z), \quad N_z = \frac{1}{2}(I_x + I_y - I_z). \tag{15}$$

The derivation is simple when writing the basic equation

$$I_x = \int_V \left(y^2 + z^2 \right) dV, \quad I_y = \int_V \left(x^2 + z^2 \right) dV, \quad I_z = \int_V \left(x^2 + y^2 \right) dV, \tag{16}$$

$$D_{xy} = \int_V xy \, dV, \quad D_{xz} = \int_V xz \, dV, \quad D_{yz} = \int_V yz \, dV, \tag{17}$$

and scaling coordinates x, y and z by scaling factors k_1, k_2 and k_3.

6. Validation

The scaling algorithm has been tested on both ROBBY2 and ROBINA reference models. Several models of various ages have been created using the reference model and the scaling algorithm. Figure 7 shows the age dependent models.

It is hard to say about the validation of the algorithm. The algorithm just updates the dimensions based on the given ones and it works. So the validation has been done in sence of validation of the sled test that has been done at the University of Heidelberg with the 13 years old boy cadaver [9]. The 13 years old boy model has been reconstructed using the 50% reference model ROBBY2 and the scaling algorithm.

The sled test has been carried out with a three point belt and standard seat. Initial position of a scaled sitting model is shown in Figure 10. Few information is available concerning the characteristics of the seat which is a drawback regarding a validation process. The deceleration pulse applied to a running seat has been taken from [9].

The model was accommodated by accelerometers giving local accelerations in head and sternum, further the belt force has been measured. The belt was simulated using the fast belt
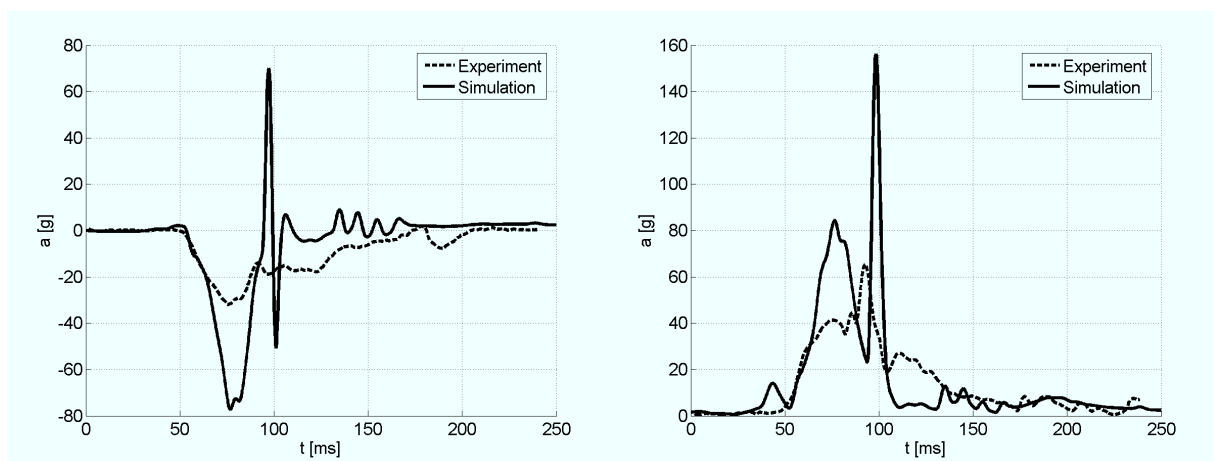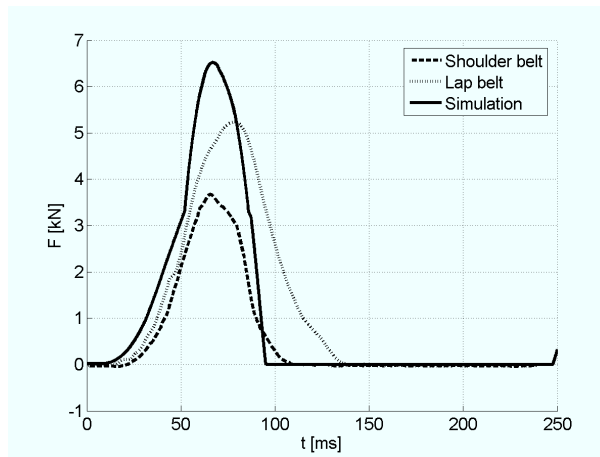
Fig. 8. Head acceleration x (left) and magnitude (right).

Fig. 9. Belt force.

system provided by the solver [1]. The airbag has been modeled using advanced airbag model provided by the solver [1]. Whole model has been pushed by initial velocity equal to the experiment and then, the experimental acceleration on the rigid seat was applied. One can see that the results summarized in Figures 8 and 9 correspond qualitatively to the experimental results.

Concerning head X acceleration in Figure 8 left, the trend of the curve is kept in sence of the experimental curve trend. There are high peaks in the beginning and around 100 ms that are probably caused by the limiting position of the neck joints. The head acceleration magnitude in Figure 8 right corresponds well during the whole simulation. The peak around 100 ms is related to the peak on Figure 8 left and is probably caused by the limiting position of the neck joints. The belt force shown in Figure 9 corresponds well from the qualitative and quantitative point of view. The higher peak is probably caused by the rigidity of the model and other parts used for the simulation. Generally, taking all simplifications of the model into account, the results seem to be in a good correlation to the experimental data [9] since non-scaled original human articulated rigid body model [7] shows similar performance. Figure 10 shows the kinematic states at 0 ms, 50 ms, 100 ms, 150 ms, 200 ms and 250 ms.
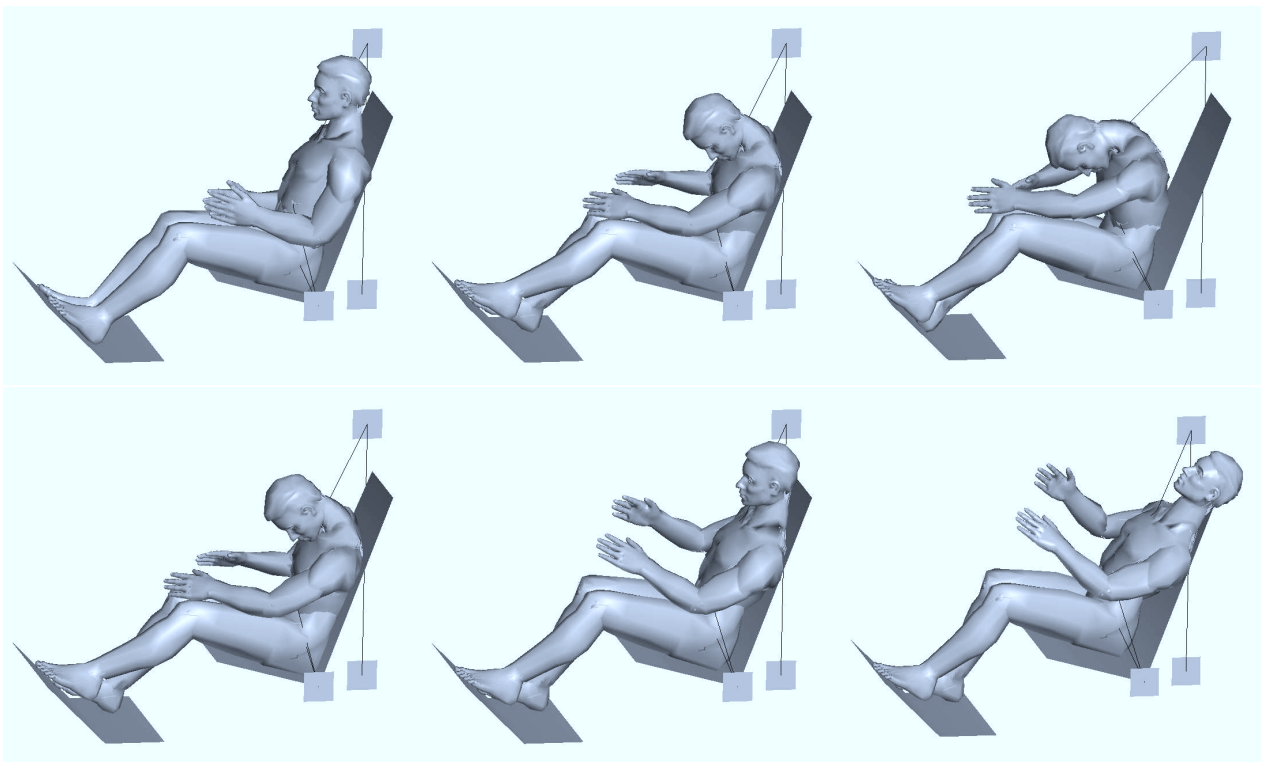
Fig. 10. Kinematic states.

7. Conclusion

Based on huge literature review, a simple scaling algorithm has been developed. The algorithm scales a reference model separated into segments connecting by joints updating its major anthropological dimensions. The application is shown in development of a 13 years old boy model that is validated in the sled test environment compared to the experimental data. Further work will be done on morphing that is necessary especially for younger population where the proportions of particular body segments are different from adult body segments.

Acknowledgment

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