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A GENERAL METHOD FOR SCALING MUSCULO-SKELETAL MODELS

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INTRODUCTION

Computer models of pure technical systems are fully established in automotive engineering, but several comfort evaluations involving human perception still require hardware and slow down the vehicle development process. Computer manikins such as Ramsis [4] are used for the analysis of vehicle package parameters. These manikins are scalable according to overall population statistics as well as detailed body dimensions. A significant portion of comfort issues are related to the muscular load situation which cannot be evaluated using Ramsis. Musculo-skeletal models are required and must possess the same scaling ability to be useful for product design. This is much more challenging, because scaling pertains not only to the overall geometry, but also to properties like muscle insertion points, muscle parameters and wrapping surfaces. A general method for scaling musculo-skeletal models is presented in this paper. The method has been implemented into the AnyBody Modeling System [2] and its associated public domain repository of models [1]. The scaling procedure is implemented in a generic manner and allows the usage of user defined scaling laws.

As an example one specific scaling law has been applied to scale the model with input data generated by Ramsis.

Figure 1: Selected members of the AnyFamily

The scaling procedures are tested for geometrical and kinematical compatibility on the so-called AnyFamily. The AnyFamily is a group of anthropometrically different models generated by Ramsis. The purpose of the AnyFamily is to provide a population representing some of the anthropometric variation of the population and thereby serves as a validation of the system's ability to scale models. Each member of the AnyFamily is represented by a list of anthropometrical data generated by Ramsis, most prominently segment lengths and masses.

METHODS

Theory of the general scaling method

This section shows the mathematical relationship between the scaled and the reference configuration. Two configurations need to be distinguished. :

1. *The reference configuration*, i.e. the existing AnyBody model, for which we know all the data that enters the model. The segments in this configuration roughly correspond to a 50th percentile European male.
2. *The scaled configuration*, i.e. the result of the scaling process. For each segment we know only some data, typically length and mass, and the remaining part of the properties must be obtained by the scaling procedure.

Linear scaling results in the following equation:

$$\mathbf{s} = \mathbf{S}\mathbf{p} + \mathbf{t} \qquad (1)$$

where $\mathbf{s}$ is the position vector of the node in the local (segment-fixed) coordinate system of the scaled segment, $\mathbf{p}$ is the original nodal location, $\mathbf{S}$ is the 3x3 scaling matrix, and $\mathbf{t}$ is a translation. The translation $\mathbf{t}$ plays the role of moving the local coordinate system relative to the actual geometry of the segment The scaling matrix, $\mathbf{S}$, takes care of the real scaling of the relative nodal position. In the following we shall make some observations about the appearance of $\mathbf{S}$ and its function: If $\mathbf{S}$ is a diagonal matrix with the same number on all diagonal places,

$$\mathbf{S} = k\mathbf{I} \qquad (2)$$

then k is the scaling ratio of the uniform scaling in all directions. If $\mathbf{S}$ is a general diagonal matrix, the scaling along the three axes of the local coordinate system will not be unique, i.e., the segment will be stretched/compressed relatively along the axes.

$$\mathbf{S} = \begin{bmatrix} k_x & & \\ & k_y & \\ & & k_z \end{bmatrix} \qquad (3)$$

Negative numbers can be used to mirror the segment (One or three negative values gives a mirrored object).
If $\mathbf{S}$ is a general orthogonal matrix,

$$\mathbf{S} = \begin{bmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \end{bmatrix}, \text{ such that } \mathbf{S}^T\mathbf{S} = \mathbf{I} \qquad (4)$$

where the vectors are basis unit vectors, then this is a rotation of the segment geometry relative to the local coordinate system. If a non-uniform scaling should be done referring to a set of axes that is not the axes of the local coordinate system, then the scaling matrix can be established by means of a transformation of the form:

$$\mathbf{S} = \mathbf{A}\mathbf{S}'\mathbf{A}^T \qquad (5)$$

where **A** is a rotational transformation matrix (orthogonal) that transforms a vector from the coordinate system in which the scaling is defined by the scaling matrix **S'** to the original local system.

Specific Length-Mass Scaling with fat percent
The general scaling strategy allows for implementation of many different specific strategies depending on the choice of scaling matrix, **S**. In this section we present one method to calculate the elements **S** for realizing the scaling based on the Ramsis data taking the weight ratio between tissue types into account.

The rationale behind this method is that there is coherence between geometry and mass of a segment. Assuming a known mass and segment length, it is possible to compute the cross sectional area. The local coordinate systems follow the ISB conventions [5]. The y-axis denotes the longitudinal direction, and x and z as the cross sectional directions. This leads to a scaling law where the y scaling differs from x and z.
We shall presume a y direction scaling of the form:

$$S_{22} = k_L = \frac{L_1}{L_0} \qquad (6)$$

Where L_1 is the segment length of the scaled segment and L_0 the segment length of the original segment. Assuming known masses the mass ratio can be obtained:

$$k_m = \frac{m_1}{m_0} \qquad (7)$$

And we subsequently get

$$S_{11} = S_{33} = \sqrt{\frac{k_m}{k_L}} \qquad (8)$$

The idea is to include the fat percent in the estimation of strength of the scaled models. The fat percent, R_{fat}, is the percentage of the entire body weight which is comprised by fat. Let us introduce the following percentages:

Organs, blood, skeleton, etc	R_{other}
Fat	R_{fat}
Muscles	R_{muscle}
Total	100%

We then get:

$$R_{muscle} = 1 - R_{fat} - R_{other} \qquad (9)$$

We can subsequently use the relationship between $R_{muscle,1}$ (for the scaled configuration) and $R_{muscle,0}$ (for the reference model) in the expression for the strength of the scaled model:

$$F = F_0 \frac{k_m}{k_L} \frac{R_{muscle,1}}{R_{muscle,0}} = F_0 \frac{k_m}{k_L} \frac{1 - R_{other} - R_{fat,1}}{1 - R_{other} - R_{fat,0}} \qquad (10)$$

where subscripts 1 and 0 represent the subject in question and for the refenerence model respectively.

The Ramsis data does not contain information about fat percent, but it might be estimated based on the body statures provided by Ramsis. Frankenfield *et al.* [3] have calculated two regression equations of the relation between Body Mass Index (BMI) and percentage of body fat, one for men and one for women.
R_{fat} for men:

$$R_{fat} = -0.09 + 0.0149 \cdot BMI - 0.00009 \cdot BMI^2 \qquad (11)$$

R_{fat} for women:

$$R_{fat} = -0.08 + 0.0203 \cdot BMI - 0.000156 \cdot BMI^2 \qquad (12)$$

BMI is defined as the ratio between body mass and the square of body height. This means that it can be computed directly from the overall body parameters of the AnyFamily members. For modeling of specific individuals, it is obviously more accurate to measure the fat percent directly.

RESULTS AND DISCUSSION
A general method of linear scaling of the nodes on segments has been developed. Despite the limitations a linear scaling can enhance the practical value of the biomechanical model. Nonlinear scaling methods require detailed information about the anatomical properties which is usually not available in practice.
Within the linear scaling one method has been derived to find the elements of the scaling matrices and the strength scale factor. This method is characterized by the fact that the fat percent is included for calculating the strength scale factor. If one does not include the fat percent than the strength of short people with a relative high mass will be overestimated. One should bear in mind that body composition at a given BMI differs across racial groups, and even within single groups there can be a quite large error in the estimation of fat percent due to different body compositions. Unfortunately the accuracy of the fat percent prediction is lowest for BMI values below 30, which encapsulates the majority of the population.

The AnyFamily verified that it is possible to use Ramsis data as input and that the scaling procedures were able to convert between models of considerable size variation. The two extremes of the AnyFamily were AnyMacy (Height: 1.52 m) and AnyJohn (Height: 1.95 m). It turned out to be no problem to scale the standard AnyBody model to AnyMacy, AnyJohn and everything in between and retain the kinematic function of the model. Whether the body strength, muscle activations and joint reactions are estimated correctly for all cases is still an open question calling for additional validation.

The scaling opens a whole new range of possibilities in applications as well as validations. It is now much more feasible to do some experiments on a certain individual and compare it with an AnyBody model, which has more or less the size of that individual. For evaluating human-machine interfaces it is obvious that the ability for testing the interface for different body sizes is really important.

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