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A General Method for Scaling Musculoskeletal Models

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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.

Kinematic computer manikins such as Ramsis are scalable according to overall population statistics as well as detailed body dimensions, but a significant portion of comfort issues are related to the muscular load situation which cannot be evaluated using kinematic tools. Musculoskeletal models are required and must possess the same scaling ability to be useful for product design.

Musculoskeletal modeling is much more challenging than mere kinematics, because scaling pertains not only to the overall geometry, but also to properties like muscle insertion points, muscle parameters and wrapping surfaces.

This poster presents a general method for scaling musculoskeletal models. The method has been implemented into the AnyBody Modeling System and its associated public domain repository of models.

The scaling procedure is implemented in a generic manner and allows the usage of user-defined scaling laws.

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.

Digital manikins
- *Ramsis*
- *Jack/Jill*
- *Delmia*

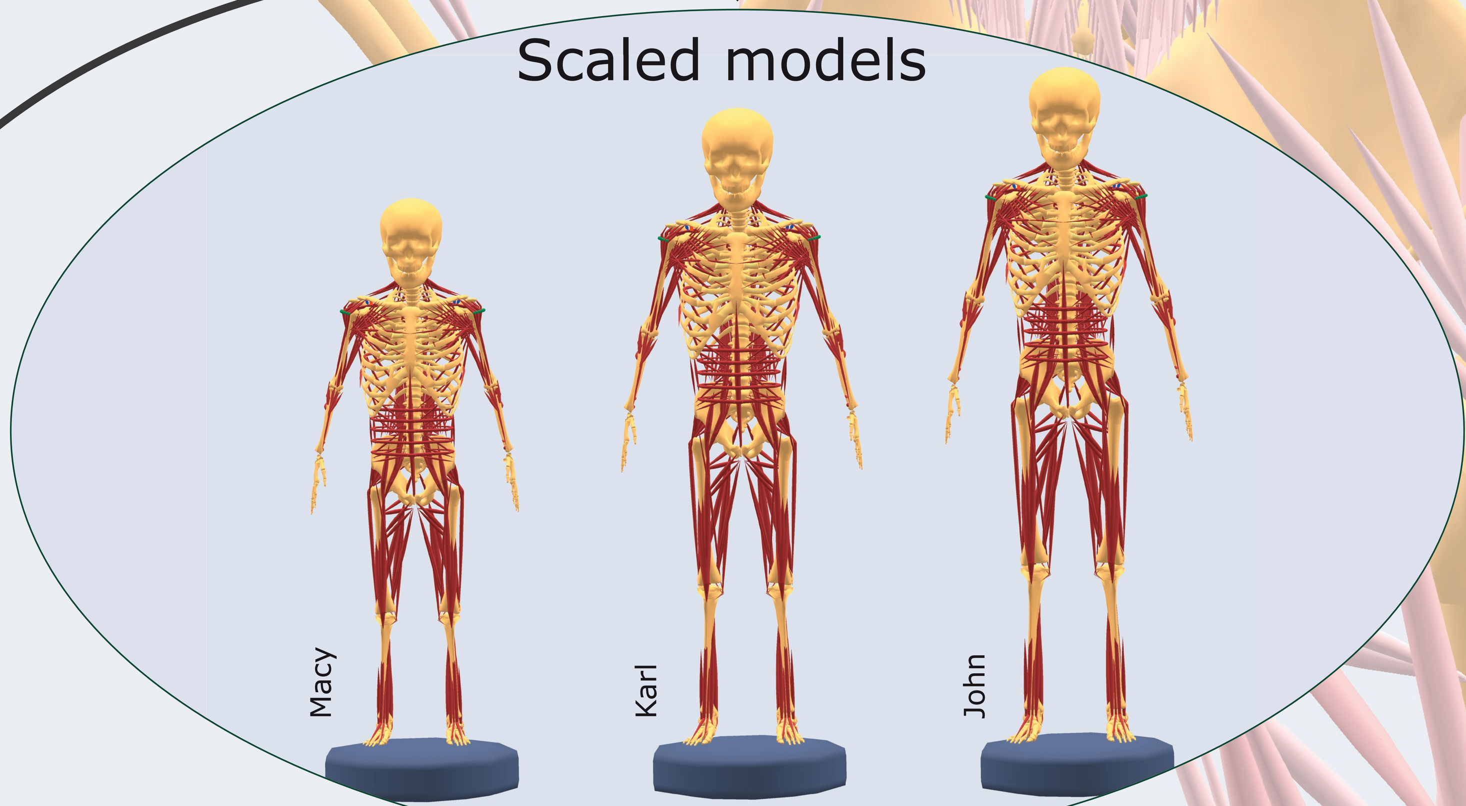
Subject data
- *Segment lengths*
- *Segment masses*

Individual measurements
- *Scans*
- *Palpation*
- *External dim's*

Population data
- *e.g. Caesar*

Scaling law:
uniform, non-uniform, mass-fat scaling
Musculoskeletal anthropometric parameters.

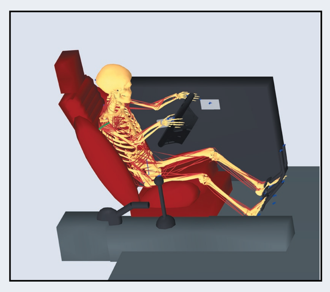
Scaled models

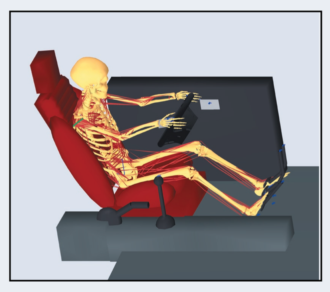


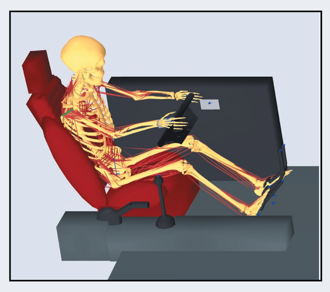
Musculoskeletal Analysis

Examples

A typical application of scaleable musculoskeletal models is for investigation of compatibility between human bodies of different sizes and car package dimensions. Traditional manikins cover the kinematical compatibility, but they do not predict the human's ability to turn a steering wheel or pull a hand brake. In these pictures, three of the family members, Macy, Karl and John, who are respectively a 5th percentile female, a 50th percentile male and a 95th percentile male, have been inserted into a vehicle package environment adjusted to normally accepted comfort positions for these percentiles.



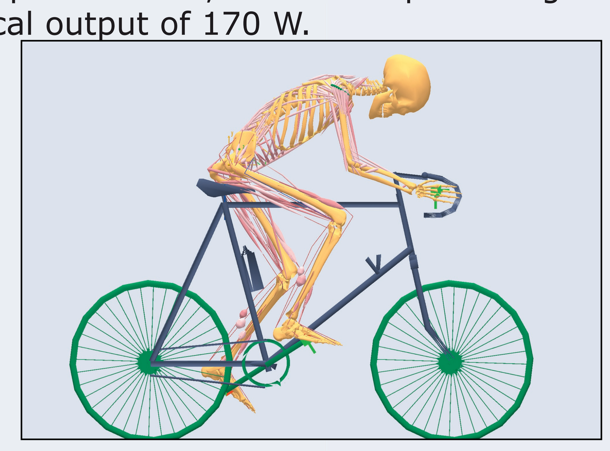




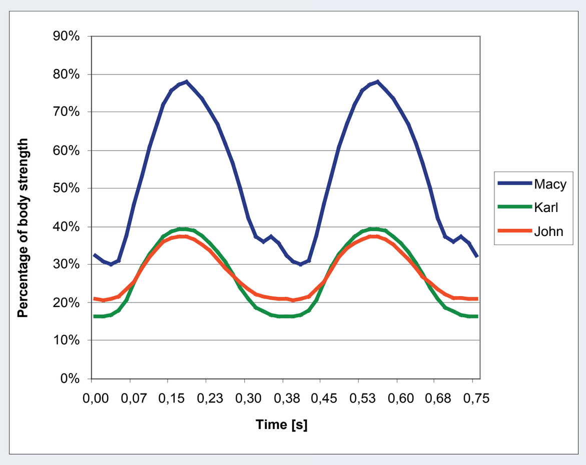
The postures of the three models adjust automatically to the package environment because of the system's ablity to model the kinematics of the environment surrounding the body as well as the body itself; the body and environment form a single mechanism.

Pedaling example

In addition to mere kinematics, the method also scales the muscle strength and is able to compute muscle forces and activities for different working tasks for differently sized models. So, for a similar work task a small female will use more of her muscular strength than a large male. In the pedaling example below, the same three family members have been seated on bicycles adjusted to their respective dimensions. The three models are subsequently required to drive the pedals with a typical crank torque variation, all of them producing an average mechanical output of 170 W.



The AnyBody Modeling System computes the activity percentage of each muscle over the crank cycle, and the maximum activity over all muscles is a good measure of how many percent of the total body strength the model is using as any given time. These activity envelopes are shown for Macy, Karl and John below.



Not surprisingly the graphs reveal that Macy must consistently use more of her strength than Karl and John to produce the same amount of mechanical power. However, notice that Karl in spite of his smaller build has a lower minimum activity than John. This happens around the dead centers of the crank cycle and is due to Karls shorter legs and consequently smaller moment arms of the pedal forces about his hip and knee joints.

Scale factors

The definition of a segment in the human model requires mass properties and in addition a number of nodes defined in the segment's local coordinate system. The nodes are used for joint centers, muscle insertions, and such. The nodes of each segment are subjected to scaling of the form

$$\mathbf{s} = \mathbf{S}\mathbf{p} + \mathbf{t}$$

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 a 3x3 scaling matrix, and $\mathbf{t}$ is a translation vector. The translation 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.

This transformation allows for non-uniform scaling rotation and translation depending on the $\mathbf{S}$ and $\mathbf{t}$, which are computed from the segment lengths and masses. Three different strategies for this computation have been attempted. They all rely on two different scaling factors:

$$k_L = \frac{L_1}{L_0} \qquad k_m = \frac{m_1}{m_0}$$

which express the scaling of segment length and segment mass respectively relative to a reference configuration.

Method 1: Uniform Scaling

This method is a uniform scaling using a diagonal matrix with the same scaling factor on all diagonal positions and an assumed relationship between muscle strength and mass based on the idea that muscle strength depends on cross sectional areas while body mass depends on volume. In other words, it presumes that the segment is scaled in all directions as it is in the length direction.

$$\mathbf{S} = \begin{bmatrix} k_L & & \\ & k_L & \\ & & k_L \end{bmatrix} \qquad F = F_0 k_m^{2/3}$$

The scaling of muscle force is nonlinear with the power of 2/3. This comes from the notion that muscle strength depends on cross sectional area while muscle weight depends on volume, and it is a rule-of-thumb within biology for scaling between spicies from insect to dinosaurs.

While this method is an obvious first choice, the uniform geometry scaling does not seem to capture the physics behind longitudinal segments whose strength and stiffness depend nonlinearly on their thickness.

Method 2: Non-uniform Scaling

This is a non-uniform scaling taking into account the fact that body segments tend to be organized with soft tissues arranged in layers around a longitudinal bone, here corresponding to the *y* axis. This idea leads to a scaling in the perpendicular directions which is square rooted and dependent on the mass as well as the length.

$$S_{11} = S_{33} = \sqrt{\frac{k_m}{k_L}} \qquad S_{22} = k_L = \frac{L_1}{L_0} \qquad F = F_0 k_m^{2/3}$$

Method 3: Mass-fat Scaling

This is a non-uniform scaling which works geometrically as method 2 but taking into account that short, heavy bodies tend to have a larger fat percentage then tall, slim bodies. The method is initially based on the observation that the total weight of the body can be divided into contributions from fat, muscle, and other tissues, where the fat percentage can either be measured directly for an individual or estimated from the body mass index, BMI, for instance as proposed by Frankenfield et al. (Nutrition. 2001 Jan;17(1):55-56). The contribution of other tissues to the body weight is estimated to be 50%. We then get:

$$R_{muscle} = 1 - R_{fat} - R_{other}$$

The muscle strength can then be estimated as:

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

Experiments show that this method tends to estimate the strength better than Methods 1 and 2.

Conclusion

Anthropometric scaling based on segment data has been implemented and results in scaling of size as well as muscular strength. Three different scaling laws, of which the mass-fat scaling is the more promising, are implemented. The muscle strength scaling needs further validation.

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AnyBody