A General Method for Scaling Musculo-Skeletal Models

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Computer models of pure technical systems are fully established in automotive engineering, but several comfort-dictating variables, implying human perception still require hardware and slow down the vehicle development process.

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

Kinesic computer modeling, such as Ramsis, is 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 kinesic tools. Musculoskeletal models are required and must possess the same scaling ability to be useful for product design.

Musculoskeletal modeling is a general tool 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 general manner which allows the use of user-defined scaling laws.

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 area while body mass depends on volume. In other words, it can be assumed that the segment is scaled in all directions as it is in the length direction.

\[
\mathbf{S} = \begin{bmatrix}
S_{11} & 0 & 0 \\
0 & S_{22} & 0 \\
0 & 0 & S_{33}
\end{bmatrix}
\]

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 species from insects to dinosaurs.

While this method is an obvious choice, the uniform geometry scaling does not seem to capture the physics behind longitudinal segments very well, and is therefore dependent on the application.

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 long, thin bone, and muscles are attached to its surface. This leads to a scaling in the perpendicular directions which is square rooted and dependent on the mass as well as the length.

\[
S_{11} = \frac{S_{d1}}{m^{1/2}} \\
S_{22} = \frac{S_{d2}}{l^{1/2}} \\
S_{33} = \frac{S_{d3}}{k^{1/2}}
\]

The muscle strength can then be estimated as:

\[
F = S_k^{2/3}
\]

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 than 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 Khamis et al. (Nutrition. 2001 Jan;17(1):55-56). The muscle percentage of other tissues to the body weight is estimated to 50%. We then get:

\[
\%\text{muscle} = 1 - \%\text{fat} - \%\text{skin}
\]

The muscle strength can then be estimated as:

\[
F = S_k^{2/3} \cdot (1 - \%\text{fat} - \%\text{skin})^{2/3}
\]

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 most common, are implemented. The muscle strength scaling needs further validation.

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