A General Method for Scaling Musculoskeletal Models

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Musculoskeletal modeling is much more challenging than mere kinematics, because scaling parameters not only act on the visual geometry, but also to properties like muscle insertion points, muscle parameters and wrapping surfaces. This paper 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 different models.

The scaling procedure is implemented in a general geometric module and allows the use of user-defined scaling laws.

Examples

A typical application of scaling musculoskeletal models is for investigation of compatibility between human bodies of different sizes and car package dimensions. Traditional manikins cover the kinematic compatibility, but they do not predict the human’s ability to turn a steering wheel or put 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 packaging environment adjusted to normally accepted comfort positions for these percentile bodies. The postures of the three models adjust automatically to the package environment because of the system’s ability to model the kinematics of the environment surrounding the body as well as the body itself; the body and environment form a single mechanism.

Musculoskeletal Analysis

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 of 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 asked to pedal a bicycle adjusted to their respective body sizes. 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.

Not surprisingly the graphs reveal that Macy must consistently use more of her strength than Karl and John. However, notice that Karl in spite of his smaller build has a lower minimum activity than John. This happens around the pedal forces about his hip and knee joints.

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 at any given time. These activity envelopes are shown for Macy, Karl and John below.

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 presumes that the scaling is a scale factor as it is in the length direction.

\[
S = \begin{bmatrix} k_1 & 0 & 0 \\ 0 & k_2 & 0 \\ 0 & 0 & k_3 \end{bmatrix}
\]

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 first choice, the uniform geometry scaling does not seem to capture the physics behind longitudinal segments whose muscle strength is dependent 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 leads to a scaling in the perpendicular directions which is square rooted and dependent on the mass as well as the length.

\[
S_1 = S_y = \sqrt{m_1}, \quad S_2 = S_z = \frac{m_2}{m_1}, \quad S_3 = k_3, \quad F = F_0 k_{3s}^{2/3}.
\]

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 more promising, are implemented. The muscle strength scaling needs further validation.

Acknowledgement

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