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A General Method for Scaling Musculoskeletal Models

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Musculoskeletal modeling is much more challenging than mere kinetics, because scaling parameters not only to the visual aspects, 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 in the AnyBody Modeling System and its associated public domain repository of models.

The scaling procedure is implemented in a generic manner and allows the user to define scaling laws. The scaling procedures are tested for geometrical and kinematic 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 set of (anthropometric) data generated by Ramsis, most prominently segment lengths and masses. This transformation allows for non-uniform scaling rotation and translation of the real scaling of the relative nodal position.

The definition of a segment in the human model requires mass properties. Three different strategies for this computation have been attempted. They all rely on two different scaling factors: length and mass. Three different strategies for this computation have been attempted. They all rely on two different scaling factors: length and mass.

Examples

Musculoskeletal parameters. 2

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 kinematic 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 20th 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 percentile individuals.

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 Karl’s shorter legs and consequently smaller moment arms of exerted force. This is using as 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 the cross sectional area while mass depends on volume. In other words, it presumes that the scaling is scaled in all directions as it is in the length direction.

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 insect to dinosaur.

While this method is an obvious first choice, the uniform geometry scaling does not seem to capture the physics behind longitudinal segments whose shape changes with the soft tissues depending 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.

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 vanwesen et al. (Nutrition. 2001 Jan;17(1):55-56). The contribution of other tissues can be measured with a high 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.

Acknowledgement

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Digital manikins
- Ramsis
- Jack/Jill
- Delmia

Population data
- e.g. Caesar

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

Scalings

Subject data
- Segment lengths
- Segment masses

Individual measurements
- Scans
- Palpation
- External dim's

Musculoskeletal Analysis

Scale factors

The definition of a segment in the human model requires mass properties and in addition a number of nodes define the segment’s local coordinate system. The model is used to load center, muscle insertions, and such. The nodes of each segment are subjected to scaling of the form

\[ S = Sp + t \]

where \( S \) is the position vector of the node in the local (segment-fixed) coordinate system of the scaled segment, \( p \) is the original node location, \( S \) is a 3x3 scaling matrix, and \( t \) 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, \( S \), takes care of the real scaling factors needed for the change.

This transformation allows for non-uniform scaling rotation and translation depending on the \( x, y, z \), which are computed from the segment length. These scaling factors allow for 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 assumed relationship between muscle strength and mass based on the idea that muscle strength depends on the cross sectional area while body mass depends on volume. In other words, it presumes that the scaling is scaled in all directions as it is in the length direction.

\[ F = F_0 \]  

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

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While this method is an obvious first choice, the uniform geometry scaling does not seem to capture the physics behind longitudinal segments whose shape changes with the soft tissues depending 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.

\[ m = \begin{bmatrix} 1 & 0 & 0 \\ 0 & m_{y} & 0 \\ 0 & 0 & 1 \end{bmatrix} \]

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

\[ F = F_0 \]

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 has been implemented are shown here. The mass strength scaling needs further validation.