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MAXIMUM HAND FORCE ESTIMATION WITH AN MRI-BASED MUSCULOSKELETAL SHOULDER MODEL

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SUMMARY

The applicability of a cadaver-based musculoskeletal model above the level of general applications is limited by the difference between the anatomy of the model and the subject or patient that is analysed. A subject-specific model should in principle perform optimally on subject-related questions, but requires the model's anatomy to be adapted to fit the specific subject. We used MRI-data to individualise one important muscle parameter of the Delft Shoulder and Elbow Model (DSEM), namely the physiological cross-sectional area (PCSA). When multiplied by maximum muscle stress (σ_{max}, generally assumed to be a constant), PCSA yields the maximum isometric muscle force. Since σ_{max} is generally assumed to be constant for human skeletal muscle, we expect to explain variations in maximum muscle forces across subjects by variations in PCSA. This is tested by calculating σ_{max} values that are required to reproduce maximum forces at the hand with three model versions of the DSEM: one that uses cadaver-based PCSA values (default model), one in which PCSAs of all muscles are scaled by a single factor per subject (uniform scaling) and one in which each muscle is scaled by a different factor (muscle-specific scaling). Scaling factors were derived from MRI-based muscle volume estimates. Strongly different σ_{max}–values were needed to reproduce force recordings of these subjects with the default DSEM (σ_{max}=94.9±32.2 Ncm^{-2}), indicating the need for individualisation. Estimates of σ_{max} were considerably more consistent (σ_{max}=62.9±4.9 Ncm^{-2}) after uniform scaling. Muscle-specific scaling did not differ significantly from uniform scaling. We explain this by a considerable inter-subject variability in parameters, other than PCSA, that contribute to relative strength in different directions such as muscle moment arms or optimum fibre lengths. We conclude that for healthy subjects, individualisation of the model's strength can most easily be done by scaling PCSA with a single factor that can either be derived from muscle volume data or from maximum strength measurements.

INTRODUCTION

One important error source of musculoskeletal models is a mismatch between the anatomy of the model, and that of the subject or patient that is analysed. This hampers the applicability of these models above the level of general applications, or "what if" questions. A subject-specific model can in principle be used on more specific, patient- or subject-related questions, but requires the model's anatomy to be adapted to fit the subject. Magnetic resonance imaging (MRI) provides detailed information of *in vivo* 3D-anatomy and can therefore be used to create subject-specific musculoskeletal models.

In this study we used MRI-data to individualise one important muscle parameter of the Delft Shoulder and Elbow Model (DSEM, [1]), namely the physiological cross-sectional area (PCSA). When multiplied by maximum muscle stress (σ_{max}), PCSA yields the maximum isometric muscle force. Since σ_{max} is generally assumed to be constant for human skeletal muscle, we expect to explain variations in maximum muscle forces across subjects by variations in PCSA. This is tested by calculating σ_{max} values that are required to reproduce maximum forces at the hand with different model versions of the DSEM, namely a version that uses cadaver-based PCSA values and subject-specific versions in which PCSAs are individualised. We expect the subject-specific versions to result in a more constant value of σ_{max}.

METHODS

Five subjects without any prior shoulder complaints, selected based on large inter-individual differences, were asked to participate in this study. The study adhered to the ethical guidelines of the 1975 Declaration of Helsinki and all participants signed for informed consent prior to the measurements.

From each subject, maximum voluntary forces on a handle gripped by the right hand with the elbow approximately 90° flexed were recorded. Subjects were asked to exert their maximal force in six different directions (to the left, right, forwards, backwards, upwards and downwards). The handle was connected to a 6-DOF force transducer that measured hand forces and moments in all three orthogonal directions during the maximal contractions.

T1-weighted axial images of the subject's right shoulders were made using a 1.5T Achieva MRI scanner (Philips Medical Systems, Best, Netherlands). The field of view (FOV) included the right half of the spine, ribcage and sternum and the complete right clavicle, scapula and humerus, as well as all muscles surrounding these bones. Muscles within the FOV were manually outlined using Amira software (Visage Imaging Inc.) and muscle volumes were calculated by summing the product of segmented area per slice and slice thickness over all slices where the muscle was visible on.

To individualise PCSA values, the ones that are used in the default DSEM (cadaver-based [2]) were scaled by multiplying with the ratio of muscle volumes and dividing

by the ratio of optimum fibre lengths between subject and default model:

$$PCSA_{subj} = PCSA_{def} \cdot \frac{V_{mus,subj}}{V_{mus,def}} \cdot \frac{\ell_{opt,def}}{\ell_{opt,subj}}$$

Two subject-specific sets were calculated:

- Uniform scaling or UNI: all muscles of a subject were scaled by the same volume factor, namely the ratio of total muscle volume between subject and default model.
- Muscle-specific or MS: each muscle was scaled by a muscle-specific factor, namely the ratio of muscle volume between subject and default model for that muscle.

The recorded external force maxima were input to the DSEM and net joint moments, muscle lengths and moment arms were calculated. Then, for each combination of subject, force direction and PCSA set, a load sharing algorithm was used to calculate the lowest possible value of maximum muscle stress that the DSEM required to be able to reproduce the recorded maximum forces of the subjects.

RESULTS AND DISCUSSION

With the default model that uses cadaver-based PCSA values, strongly different values for σ_{max} were required to reproduce the recorded maximum hand forces for different subjects (σ_{max}=94.9±32.2 Ncm^{-2}, see Figure 1). The standard deviation across subjects dramatically reduced from 33.9% of the mean value for the default model to only 7.8% of the mean after scaling with a single factor (UNI: σ_{max}=62.9±4.9Ncm^{-2}). Muscle-specific scaling did not lead to any significant differences compared to uniform scaling (MS: 63.4±4.3Ncm^{-2}).

As expected, uniform scaling led to a more consistent prediction of σ_{max}, which indicates that the scaled model can account for inter-individual differences in maximum strength. As the muscle-specific scaling method scales different muscle(s) (groups) differently, we expected this version to lead to a more consistent value of σ_{max} across force directions, but this was not the case. We explain this by a larger contribution of other factors that were not accounted for, such as inter-individual differences in optimum fibre lengths or muscle moment arms.

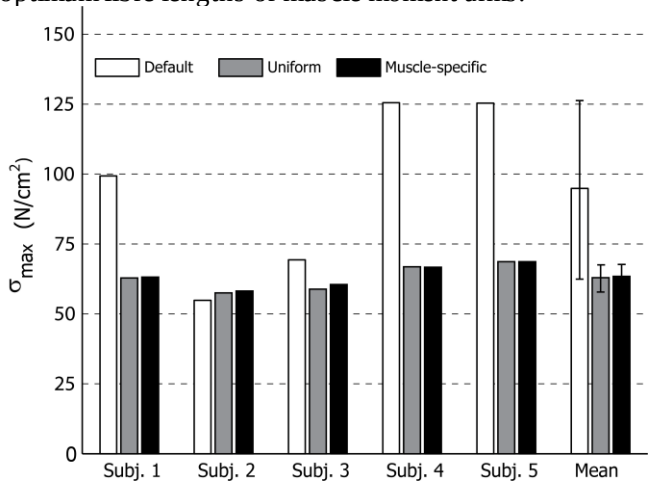

Figure 1 Maximum muscle stress required to reproduce the maximum hand force of different subjects with the default, the uniformly scaled and the muscle-specifically scaled model.

Further analysis of the muscle volume data revealed that muscle volumes are strongly different across the subjects we analysed (factor 2.5 between the subject with the lowest and highest muscle volume), but very consistent when expressed as percentage of the total muscle volume of a subject. This explains also why uniform scaling did not lead to any significant differences from muscle-specific scaling.

We also found that total muscle volume of the analysed subjects correlate very well with their maximum force (R^2=0.975, Figure 2). This explains why scaling the model according to muscle volume data leads to a more consistent value of σ_{max}.

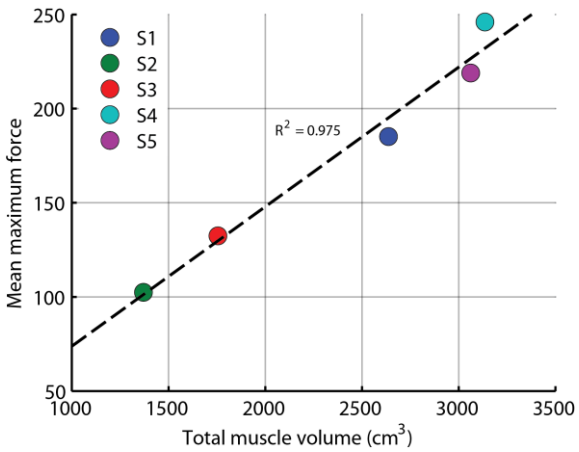

Figure 2 Maximum strength at the hand vs. total shoulder muscle volume.

In this study we showed one important feature of a subject-specific model, namely that it is more capable of accounting for inter-individual differences than a generic model. We also showed that a simpler scaling routine is not superior to a more advanced method. A limitation of MRI-based musculoskeletal modelling is that muscle properties like optimum fibre lengths or moment arms are much more difficult to derive than muscle volumes. These should therefore either be scaled from cadaveric values, or new methods for *in vivo* estimation of these properties should be developed.

It is not known to what extent the results of this study that was performed on a young, healthy population are also valid for elderly people or patients.

CONCLUSIONS

Based on the results of this study, we conclude:

1. By scaling PCSA from muscle volume data, a musculoskeletal model can account for inter-individual differences in maximum strength.
2. Scaling with one factor per subject is similar to scaling each muscle separately.
3. Shoulder model strength can be scaled either from muscle volume data or from strength tests.

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