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The effect of scaling physiological cross-sectional area on musculoskeletal model predictions

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ABSTRACT

Personalisation of model parameters is likely to improve biomechanical model predictions and could allow models to be used for subject- or patient-specific applications. This study evaluates the effect of personalising physiological cross-sectional areas (PCSA) in a large-scale musculoskeletal model of the upper extremity. Muscle volumes obtained from MRI were used to scale PCSAs of five subjects, for whom the maximum forces they could exert in six different directions on a handle held by the hand were also recorded. The effect of PCSA scaling was evaluated by calculating the lowest maximum muscle stress (σ_{max}, a constant for human skeletal muscle) required by the model to reproduce these forces. When the original cadaver-based PCSA-values were used, strongly different between-subject σ_{max}-values were found ($\sigma_{max}=106.1\pm39.9$ N cm^{-2}). A relatively simple, uniform scaling routine reduced this variation substantially ($\sigma_{max}=69.4\pm9.4$ N cm^{-2}) and led to similar results to when a more detailed, muscle-specific scaling routine was used ($\sigma_{max}=71.2\pm10.8$ N cm^{-2}). Using subject-specific PCSA values to simulate an shoulder abduction task changed muscle force predictions for the subscapularis and the pectoralis major on average by 33% and 21%, respectively, but was $<10\%$ for all other muscles. The glenohumeral (GH) joint contact force changed less than 1.5% as a result of scaling. We conclude that individualisation of the model's strength can most easily be done by scaling PCSA with a single factor that can be derived from muscle volume data or, alternatively, from maximum force measurements. However, since PCSA scaling only marginally changed muscle and joint contact force predictions for submaximal tasks, the need for PCSA scaling remains debatable.

1. Introduction

All musculoskeletal models available today use at least some data derived from cadaver experiments to predict immeasurable, though clinically relevant, muscle and joint contact forces. Reducing the morphological differences between the model and the subject or patient to be analysed is likely to result in model predictions with smaller error margins and therefore a wider application range of these models. Patient- or subject-specific musculoskeletal modelling is therefore a hot topic, but still many difficulties exist, causing applications to be almost non-existent for large-scale upper extremity models (Bolsterlee et al., 2013).

The level of subject-specific detail can affect model outcome (Scheys et al., 2011, 2008b) and methods ranging from relatively simple scaling methods (Matias et al., 2009) to full three-dimensional reconstruction of *in vivo* bony anatomy from for example MRI or CT scans (Krekel et al., 2009; Scheys et al., 2008a) have been developed. Still problematic is the scaling of soft tissue parameters, though this is required to maintain consistency in model parameters when scaling bone geometry (Praagman et al., 2010; Winby et al., 2008). The topic of the present study is the effect of personalising physiological cross-sectional area (PCSA) on musculoskeletal model predictions of the upper extremity (Nikooyan et al., 2011b). PCSA is one of the muscle parameters that strongly varies between subjects and muscles (Holzbaur et al., 2007) and is proportional to maximum muscle strength (Powell et al., 1984).

The goal of scaling is to increase model applications by improving relevant model estimations, but this cannot yet be assessed at individual muscle force level due to the complexity of measuring these forces non-invasively. By comparing to *in vivo* measurements of glenohumeral (GH) joint contact force, it was found that an upper extremity model overestimates the joint force

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by 34% during maximum force tasks (Nikooyan et al., 2010). It was suggested that this could be improved by personalising PCSA. Because GH joint forces are not available for healthy subjects, in the present study we use external force measurements at the hand, which is also the result of the combined action of individual muscles. Previously it was found that predictions of a shoulder model could more closely match experimental recordings of maximum strength in different directions after altering PCSA values (Makhsous et al., 1999), but these variations were not verified against *in vivo* measured PCSAs.

In the present study, we scale PCSA from muscle volume data obtained from MRI. We use a unique approach based on muscle load sharing to calculate the maximum muscle stress (σ_{max}) that is required by the model to reproduce the maximum forces that subjects could exert on a handle held by the hand. Two scaling routines are tested: a simple, uniform scaling routine (all muscles scaled by one factor per subject) that is relatively easy to implement in practice and a muscle-specific routine (each muscle scaled by a separate factor) that requires more detailed, subject-specific information. Both σ_{max} and PCSA are proportional to maximum strength, but where PCSA is known to vary substantially between subjects, σ_{max} is generally assumed to be a constant for human skeletal muscle, although the exact value is subject of debate. It is hypothesised that PCSA scaling can account for inter-subject variation in maximum strength, reflected in a small inter-subject variation of σ_{max}. Furthermore, we expect that muscle-specific scaling can better predict maximum strengths in different directions than uniform scaling (reflected in a more constant σ_{max} across directions), because it accounts, in contrast to uniform scaling, for inter-individual variations in PCSA distribution among muscles.

2. Methods

Five subjects without any prior shoulder complaints participated in this study (Table 1) after having given informed consent. The study was approved by the institutional ethical committee. The experimental protocol encompassed the collection of functional data (maximum forces) and image data (MRI scans). Model simulations were performed with the Delft Shoulder and Elbow Model (DSEM; Nikooyan et al., 2011b).

2.1. Functional data

Each subject was instructed to exert maximum force in six different directions on a handle that was gripped by the right hand, while standing with the elbow 90° flexed (Fig. 1). Contact between thorax and elbow was avoided. Subjects were instructed to gradually build up force (within a few seconds) and then maintain their maximum for approximately three seconds. The order of force exertion was: upwards (UP), downwards (DOWN), forwards (FORW), backwards (BACK), to the left (LEFT) and to the right (RIGHT). Ten seconds rest was given between subsequent directions. After three minutes rest this procedure was repeated. No feedback on force magnitude or direction was given. Forces and moments exerted on the handle were measured in three perpendicular directions (sample frequency 1000 Hz) with a (calibrated) six-DOF force transducer (SRMC3A, Advance Mechanical Technology Inc., USA) that was connected to the handle. For model simulations (see Section 2.3), all components of these forces and moments were used.

Per subject, direction and trial, the maximum force, defined as the maximum averaged force over 100 subsequent samples (100 ms), was computed. Only the maximum value of both trials was used for further analysis (Table 1).

During the force measurements, the positions of five marker clusters attached to thorax, scapula, humerus, forearm and hand were tracked using an Optotrak system (Northern Digital, Inc., Waterloo, Canada). Prior to the force measurements, bony landmarks as proposed by the ISB (Wu et al., 2005) were palpated by the endpoint of a stylus, while recording positions of marker clusters and the markers attached to the stylus. The GH joint centre was determined using the instantaneous helical axis method (Nikooyan et al., 2011a). From the locations of bony landmarks, local coordinate systems and orientation angles were derived according to the ISB convention (Wu et al., 2005).

Table 1
Anthropometrics and maximum voluntary forces for all directions and subjects.

	S1	S2	S3	S4	S5	Mean ± SD
Gender	M	F	F	M	M	–
Age (yr)	29	29	27	33	28	29.2 ± 2.3
Body weight (kg)	109	60	79	69	81	79.6 ± 18.5
Height (cm)	186	168	171	180	177	176.4 ± 7.2
Maximum forces (N)[a]						
LEFT	177.4	85.4	103.2	209.0	208.2	156.6 ± 58.6
RIGHT	135.4	46.7	70.5	186.7	147.4	117.3 ± 57.5
UP	186.9	105.3	170.6	271.8	263.0	199.5 ± 69.2
DOWN	154.6	94.6	118.9	182.3	221.3	154.3 ± 50.2
FORW	179.9	152.5	149.6	259.8	185.8	185.5 ± 44.5
BACK	276.7	129.9	181.7	366.5	288.0	248.6 ± 93.3
Mean per subject	185.2	102.4	132.4	246.0	218.9	

[a] Per direction, only the component of the force in that direction is presented here, but because no feedback on the direction was provided, the subjects could deviate from this direction. All force components were measured and used in the simulations.

2.2. Image data and PCSA scaling

Axial images of the subjects in the supine position were obtained with a 1.5 T Achieva MRI scanner (Philips Medical Systems, Best, Netherlands), using a 16 element XL Torso coil and the following settings: turbo-spin echo sequence (TSE) with TE/TR = 20/554 ms, acquisition matrix = 360 × 600, bandwidth 260 Hz, FOV 180 × 180 mm^2, slice thickness 3 mm. The field of view included the right half of the spine, ribcage and sternum and the complete right clavicle, scapula and humerus, as well as most of the muscles surrounding these bones (Fig. 2). Muscles that were visible on the scan were manually outlined using ZIBAmira 2011 (Zuse Institut Berlin, Berlin, Germany). Muscle volumes were calculated by summing the product of segmented area per slice and slice thickness over all slices containing the muscle (Table 2).

The model parameters as used in the default DSEM all stem from the same cadaver (Klein Breteler et al., 1999; Minekus, 1997). Muscles with large attachment sites (for example deltoid, trapezius, and subscapularis) were subdivided in multiple elements during the cadaver measurements and parameters for each element were obtained (Table 3). The model that uses this dataset will be referred to as the default model.

PCSA is defined as muscle volume divided by optimum fibre length. To obtain subject-specific PCSA values, the default ones were scaled by multiplying by the ratio of muscle volumes and dividing by the ratio of optimum fibre lengths between subject and default model.

$$\mathrm{PCSA}_{\mathrm{subj}} = \mathrm{PCSA}_{\mathrm{def}} \cdot \frac{V_{\mathrm{mus,subj}}}{V_{\mathrm{mus,def}}} \cdot \frac{\ell_{\mathrm{opt,def}}}{\ell_{\mathrm{opt,subj}}} \quad (1)$$

where V_{mus} denotes muscle volume, ℓ_{opt} denotes optimum fibre length and subscripts 'subj' and 'def' denote 'subject' and 'default', respectively. Two scaling methods were applied, leading to two different sets of PCSA values per subject (Table 3):

- Uniform scaling: all muscles for a subject were scaled by the same volume factor, namely the ratio of total muscle volume (sum of volumes of muscles that are visible on the scan) between subject and default model.
- Muscle-specific scaling: each muscle that was visible on the scan was scaled by a muscle-specific factor, namely the ratio of muscle volume between subject and default model for that specific muscle.

Because optimum fibre length cannot be obtained from MRI and there is no general scaling rule available, we assumed proportional scaling of optimum fibre lengths with bone dimensions. This scale factor, $\ell_{opt,def}/\ell_{opt,subj}$, was approximated by the ratio of humerus length ℓ_{hum} for upper arm muscles, radius length ℓ_{rad} for forearm muscles and clavicle length ℓ_{clav} for muscles that have their primary orientation from medial to lateral (in the frontal or coronal plane) (Table 3). Muscle mass, a parameter that is used by the load sharing algorithm of the DSEM, was scaled by multiplication with $V_{mus,subj}/V_{mus,def}$.

2.3. Model simulations

The DSEM (Nikooyan et al., 2011b; Van Der Helm, 1994) is a musculoskeletal model that simulates the mechanical interaction between skeletal motions and muscle activations in the human shoulder and elbow. The model comprises the thorax, clavicle, scapula, humerus, radius and ulna and all muscles that cross the joints connecting these bones. Muscles are modelled as force-generating, one-

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