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DETERMINING SUBJECT-SPECIFIC PCSAS FOR MUSCLES OF THE FOREARM

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SUMMARY

Physiological cross-sectional area (PCSA) is a very important parameter for modeling muscle force. Most studies utilize cadaveric data when doing so, however, it is not known how appropriate this is for forearm muscles. In this study, the volumes of four forearm muscles were determined using 3D parametrized (finite element) models created with the data derived from Magnetic Resonance Imaging (MRI). These subject-specific muscle volumes were used to calculate the PCSAs of the muscles, and the results are presented.

INTRODUCTION

Muscle forces are a fundamental element in the study of human movement. The forces generated by muscles create the joint torques that make movement possible. However, due to the difficulty in evaluating muscle forces in vivo, and their absence in a natural state in vitro, there remains a limited understanding of their roles at many joints.

The forearm consists of 19 muscles, with an additional 4 upper arm muscles that insert onto forearm bones. While functions have been suggested for these muscles based on their location and anatomy, the way in which they mediate forearm rotation is not well understood. This inadequate understanding limits the ability of clinicians when treating debilitating disorders and injuries of the forearm.

Physiological cross-sectional area is defined as the cross-sectional area of a muscle, perpendicular to its fiber orientation, and is strongly related to the maximal force a muscle can produce [4]. It is, therefore, an important variable in muscle force modeling. PSCA data for forearm muscles have been reported in cadaveric studies [5,6]. However, it is not known how well these values reflect the muscles of living individuals, particularly of a different ethnic or morphologic type.

This study aimed to determine a subject-specific PCSA for forearm muscles using MRI data and finite element modeling (FEM).

METHODS

The forearm of a 27 year old healthy male participant was held in a neutral position using a specially designed jig, and scanned using a 3T Siemens Skyra MRI Scanner. The acquired images were T1-weighted, with an in plane resolution of 0.5625mm and a slice thickness of 3mm.

Four forearm muscles were included in this initial work: Brachioradialis (BRAR), Flexor Carpi Ulnaris (FCU), Extensor Carpi Ulnaris (ECU), and Pronator Quadratus (PQ). These muscles were segmented from the MRI data using in-house bioengineering modeling software CMISS (www.cmiss.org), and the resulting data clouds were used to create 3D finite element models of each of the muscles (Figure 1).

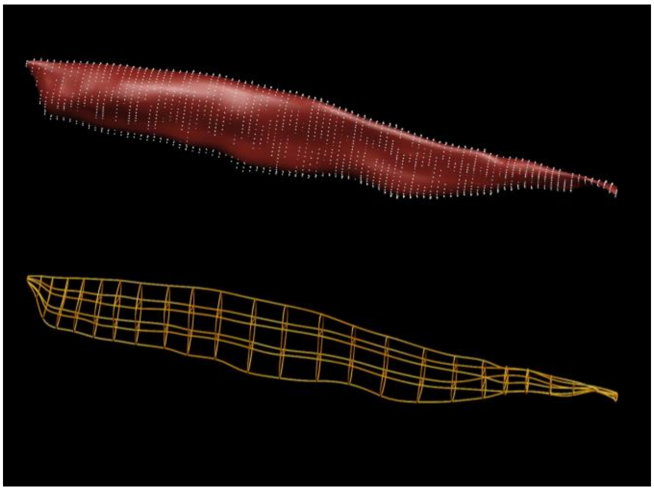

Figure 1: Data points segment for FCU from MRI images, and used to construct a 3D FE model.

The volume of each muscle mesh was numerically evaluated using the Gauss-Legendre quadrature. The maximum anatomical cross-sectional area (ACSA) was also determined. Mean muscle fiber lengths were obtained from a cadaveric study [5,6], and used to calculate PCSA with the following equation [1]:

$$\mathrm{PCSA} = \frac{\mathrm{Muscle Volume}}{\mathrm{Mean\ Fibre\ Length}}$$

The PCSA of each muscle was also multiplied with the cosine of its pennation angle (θ) to relate its total force generating capacity to the force that would be transferred to the tendon [8]. Pennation angles were obtained from a cadaveric study [5,6].

RESULTS AND DISCUSSION

The results are presented in Table 1. The muscle volumes calculated in this study were 1.5 to 3.7 times greater than those that have been calculated from cadaveric measures [5,6]. This is consistent with the results of similar studies carried out on the lower limb [3]. These results indicate that the muscle volumes of healthy, young individuals can be significantly different to the muscle volumes of the populations typically used in cadaveric studies.

As would be expected from these larger muscle volumes, the PCSA values for these muscles were also much larger than those previously reported [5,6]. While inter-individual variation can't be shown from these results, it is clear that an individual's forearm muscle PCSAs can differ substantially from cadaveric data. This may significantly affect subsequently calculated muscle forces.

Many studies have included pennation angle in their calculation of PCSA [5,7]. The FCU has a pennation angle of approximately 12°, which is the greatest reported for forearm muscles. However, its pennation angle will only cause a 2% change in the PCSA calculation. This negligible effect was shown in our results (Table 1).

The present study relied on cadaveric data for mean fiber length. The fiber lengths of these muscles are very consistent across studies [2,5,6], however, in vivo estimates could provide more accurate PCSA values.

Previous studies have reported that, while the absolute PCSAs can differ significantly, the relative values of muscles in a group remain similar to those reported in cadaveric studies [3]. This can't be evaluated for the forearm until the remaining muscles have been studied, but these early results suggest that this will not be the case. The FCU has a far larger, and the ECU a far smaller relative PCSA than was reported in cadaveric data. It is possible that younger, healthier subjects will show a greater variability in muscle size compared with cadaveric populations. More individualized estimates of PCSA may then be necessary for forearm models.

CONCLUSIONS

The results of this study show an underestimation of forearm muscle volumes in cadaveric data. This is consistent with previous research into other muscle groups. The larger muscle volumes result in a larger PCSA calculation, which may have a significant effect on muscle force predictions. In vivo PCSA calculations for the remaining muscles of the forearm and for a larger number of individuals would provide more realistic input for use in forearm models.

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Table 1: Muscle volumes and ACSAs calculated for the four forearm muscle models, mean fiber lengths and pennation angles taken from literature, and the resulting PCSA and PCSA x cosθ values calculated.

Muscle	Volume (cm^3)	Fiber Length (mm)	Pennation (°)	ACSA (mm^2)	PCSA (mm^2)	PCSA x cosθ (mm^2)
BRAR	58.9	112.0	2.0	487	487	487
ECU	18.9	50.7	3.5	172	373	372
FCU	45.8	41.5	12.1	276	1105	1080
PQ	13.4	23.0	10.0	437	583	574