INTRODUCTION

Traditionally muscle pennation angles are either measured on the surface of a dissected muscle using a goniometer [1], or measured in vivo using an imaging technique such as ultrasound [2] which displays a single cross-section of muscle. Magnetic Resonance Imaging (MRI) produces images throughout the muscle in the three planes and in two of the planes (frontal and sagittal), pennation angles can be measured. By measuring the pennation angle in both planes for all images, the variability of pennation angle can be quantified. The purpose of this study was to describe the variability of pennation angle observed throughout the First Dorsal Interosseous (FDI) muscle. Pennation angles were measured using MRI of the FDI muscle.

METHODS

One FDI muscle was removed from each of two embalmed cadavers for a total of two FDI muscles. Each muscle was removed using the methods described in Infantolino and Challis [1] to ensure complete removal of the muscle and the tendon. The cadaver characteristics were: Cadaver 1: female, 76 years old, 152 cm in height, 67.37 kg in mass, cause of death – end stage congestive heart failure; Cadaver 2: male, 72 years old, 160 cm in height, 72.60 kg in mass, cause of death – esophageal carcinoma.

To reduce the MRI scanning time the tissue was immersed in a 1.5% Magnevist (Bayer Health Care, Wayne, NJ) phosphor-buffered saline solution for 7 days. The achieved short T1 (33 ms) and T2 (7 ms) times allowed for fast imaging with a high contrast-to-noise ratio. To prevent the tissue from drying out and to minimize magnetic susceptibility artifacts during scanning the specimens were surrounded by a flourinert liquid FC-43 (3M, St. Paul, MN). All experiments were conducted using a vertical wide bore 14.1 tesla Varian MRI system (Varian Inc., Palo Alto, CA) with direct drive technology. A commercially available millipede resonator (Varian) with an inner diameter of 40 mm was used to acquire three-dimensional spin echo images of the muscle tissue. A standard imaging experiment with an isotropic resolution of 75 μm comprised a field of view of 45 x 20 x 20 mm³ and a matrix size of 600 x 268 (75% partial Fourier: 201) x 268. With 12 averages and a repetition time of 75 ms (echo time 11.7 ms) the total scan time was 13.5 hours. MATLAB (The MathWorks, Inc., Natick, MA) was used for post-processing. By zero-filling each direction by a factor of two the pixel resolution of the standard imaging experiment was 37.5 μm isotropically.

The software Mimics (Materialise, Leuven, Belgium) was used to measure the pennation in each image for the medial-lateral and anterior posterior image planes (37.5 μm thick slices). One angle measurement was taken along the medial-lateral axis (Figure 1) while two measurements were taken along the anterior-posterior axis for each slice (Figure 2) because of the two headed nature of the muscle. Measures of pennation were made with an attempt to use the same location in the muscle throughout the different slices. In addition, for one image in each imaging plane the pennation angles of all fibers were measured. This was to demonstrate the variability in pennation angles that could be measured within the same image. In this case the measures were made in a plane which approximates the superficial surface used when making measures on cadavers using a goniometer.
RESULTS AND DISCUSSION

Along the medial-lateral axis the first cadaver muscle was 16.8 mm long (448 slices), while in the second it was 10.8 mm long (287 slices). In the anterior-posterior axis the first muscle was 11.4 mm long (305 slices) and the second cadaver muscle was 8.9 mm long (237 slices).

Nearly all the pennation angles throughout the muscle demonstrated non-normal distributions assessed using an Anderson-Darling statistic ($p < 0.05$ for all measures but one). The multiple pennation angle measures in one image demonstrated a coefficient of variation of 57% for the medial-lateral axis, 33% for the first metacarpal head of the FDI, and 19% for the second metacarpal head of the FDI for the first cadaver. All of these measures demonstrated normal distributions. This variability in pennation angle has functional significance as pennation angles were measured above $15^\circ$ which is the angle at which Zajac [3] stated that pennation angle makes a contribution to muscle force production.

CONCLUSIONS

The non-normal distribution of pennation angles in an anatomical plane hints at a more complex distribution of fascicles than assumed when a single pennation angle is used to represent an entire muscle. Therefore, this distribution indicates that a single pennation angle may not be an appropriately measure to describe the arrangement of muscle fascicles in a whole muscle. The multiple measures of the pennation angles within one image demonstrate that many pennation angles can be observed and these pennation angles can vary by an amount that can have functional significance.

REFERENCES