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VALIDITY AND RELIABILITY OF FOOT MUSCLE VOLUME DETERMINATION BY MAGNETIC RESONANCE IMAGING

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SUMMARY
The purpose of this study was to demonstrate the validity and reliability of using Magnetic Resonance Imaging (MRI) to quantify human intrinsic foot muscle volumes *in-situ*. Validity was assessed by comparing MRI based muscle volumes against dissection based muscle volumes in five cadaveric feet. The reliability of MRI scanning of the foot was assessed by comparing muscle volumes in two scans of the same human subject, 11 weeks apart. We demonstrate excellent validity and reliability parameters for the use of MRI in quantifying *in-situ* muscle volumes.

INTRODUCTION
The ability to quantify skeletal muscle volume *in vivo* has become important in several key areas pertaining to musculoskeletal research. Muscle volume is used to determine the efficacy of strength training interventions[1-3], adaptations to space flight[4], and effects of aging and resistance training in the elderly.[5, 6] It is also important for biomechanical models that require accurate measurements of muscle size (mass or volume) to improve the predictive power of mechanical force estimates.[7, 8] More recently, there has been a growing necessity for a valid technique to measure the volume of the intrinsic foot muscles *in vivo*, in order to quantify the hypertrophic effects of training regimens[9, 10], as well as the atrophic effects of pathologies like diabetic neuropathy[11] and plantar fasciitis.[12] There is only one previous intervention study that has quantified adaptations to intrinsic foot muscles in response to training.[9, 10], but reliability and validity were not established. Importantly, it has been demonstrated that muscle volumes cannot always be accurately measured.[13] While MRI is the most suitable tool for this purpose (because of high tissue contrast and no ionizing radiation exposure to the patient), there is no current data on the validity and reliability of using MRI to determine foot intrinsic muscle volume. Therefore, the purpose of this study was to provide validity and reliability data to justify the use of MRI for *in-vivo* volumetric analysis of intrinsic foot muscles.

METHODS
This study was designed according to the methods described by Eng et al. (2007)[13]. Five cadaveric feet (Average age 90.6 years; 4 female, 1 male) were separated 5cm proximal to the medial malleolus. MR images of each foot were obtained using a 3.0 T Signa HDxt MR imaging system (GE Medical Systems, Milwaukee, WI). Images were acquired in the sagittal plane using a three-dimensional (3D) fast-spoiled gradient recalled echo (FSPGR) T1 weighted pulse sequence that provides an isotropic voxel dimension of 1 mm^3, and good contrast between muscle and fascia (Ankle protocol, repetition time=6.46ms, echo time=2.1ms, averages=1, slice thickness=1mm, gap between slices=0 mm, reconstruction diameter=250×250mm, display matrix= 512×512 phase FOV=1, flip angle=25°, acquisition matrix=320×320, NEX=1, EC= 1/1, Bandwidth=31.25, scan time=7.82min, images=252 and an eight-channel HD phased array brain coil). This pulse sequence was chosen because it gave us superior tissue contrast, spatial resolution, and low scan times compared to traditional 2D Fast Spin Echo sequences. In order to quantify spatial distortions within the field of view, two water phantoms were scanned. A plastic pipe with 42 ml distilled water was placed in the same axis as the foot, and another 20 ml phantom was placed orthogonally. Additionally, two scans were obtained 11 weeks apart on the dominant foot of one human subject, using the same scanning protocol. Muscle volumes were measured from 3D image data sets in the three cardinal planes manually, using ImageJ (NIH, Bethseda, MD), OsiriX DICOM viewer (Pixmeo, Switzerland) and SliceOmatic (TomoVision, Canada) software. Individual muscles were outlined and subsequently the cross sectional areas (CSA) were calculated. Muscle volumes were calculated (Muscle Volume = CSA x slice thickness x number of slices) for the following individual muscles: Abductor hallucis, Quadratus plantae, Abductor digiti minimi, and Flexor digitorum brevis.

After scanning and image processing, the feet were dissected and the muscles removed. The excess fat, fascia, and external tendons were dissected off the muscles. Each muscle was weighed to the nearest 0.01 g and its volume calculated using a density value appropriate for 5% Formaldehyde fixation.[14] The degree of agreement between dissection and MR-based volume measurements was calculated using $ICC_{(2,1)}$ at $\alpha<0.05$ significance, and the relative error between measurement techniques

through percent differences. Test-retest intra-examiner reliability $ICC_{(2,1)}$ was determined by comparing the assessed MRI muscle volumes measured 11 weeks apart.

RESULTS AND DISCUSSION

Phantom testing demonstrated low spatial distortions within the field of view. Both in-plane and out-of-plane linear measurement errors for the two phantoms were 1% at maximum (25 measurements). This result contrasts with the hardware related errors demonstrated by Eng et al.(2007) when using a different coil.[13]

There was excellent agreement between the measurement techniques for the Abductor hallucis $ICC_{(2,1)}$ = 0.91, average percent difference 3.6%; and Abductor digiti minimi $ICC_{(2,1)}$ = 0.92, average percent difference 4.5%. There was good agreement between measurement techniques for the Quadratus plantae $ICC_{(2,1)}$ = 0.80, average percent difference 6.4%; and Flexor digitorum brevis $ICC_{(2,1)}$ = 0.74, average percent difference 9.2%. The lower level of agreement is mostly due to manual segmentation errors owing to the difficulty in accurately defining the smaller muscles. Test-retest reliability for a single examiner was excellent ($ICC_{(2,1)}$ = 0.98, average percent difference 2.2%) for the Abductor hallucis and Abductor digiti minimi. The reliability was lower ($ICC_{(2,1)}$ = 0.94, average percent difference 4.2%) for the Quadratus plantae and Flexor digitorum brevis. These reliability results are comparable with what has been reported for the human forearm.[13]

CONCLUSIONS

MRI based *in-vivo* measurement of intrinsic foot muscle volumes is valid and reliable, within the constraints of the required hardware. This study will encourage the design of prospective studies that track intrinsic foot muscle volumes across various fields of musculoskeletal research.

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