Real-time measurements of knee muscle moment arms during dynamic knee flexion-extension motion

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Introduction. Accurate descriptions of muscle-tendon moment arms are needed to characterize muscle function. The moment arm of a muscle affect the muscle's ability to generate force, produce joint moments, and actuate movement. However, moment arms are challenging to measure robustly, as they may vary substantially with body position and loading condition, especially for muscles that have complex path geometry. Most estimates of muscle moment arms are based on cadaveric measurements [e.g., 2]; however, *in vivo* approaches are needed to characterize moment arms in more representative subject populations and for physiologic ranges of motion and loading conditions. Ultrasound techniques have been used to characterize *in vivo* moment arms under physiologic loading conditions [3]; however, they are limited to planar measurements and can only be used to study small regions of superficial muscles, limiting the ability to study long muscles that have complex paths. The goal of this study was to evaluate the feasibility of measuring knee muscle-tendon lengths and moment arms over a full range of motion using real-time MRI in a 70cm bore scanner.

Methods. We acquired real-time gradient-echo sagittal-plane images (6 frames per second, 42cm by 31.5cm FOV, 128 by 96 matrix, 9mm slice thickness, and a 30° flip angle) of the knee in a Siemens Espree 1.5T 70cm bore scanner, which allows for substantially larger range of motion than that allowed in a traditional 1.5T bore. The subjects flexed and extended their knees through a ~140-degree range of motion at about 8 cycles per minute. In each real-time frame, the path of the rectus femoris muscle was digitized and the knee flexion angle was measured (Fig. 1A-C). Based on the digitized paths and angle measurements, we determined the muscle-tendon length (l^{mt}) as a function of knee flexion angle (θ). The muscle moment arms (*ma*) were determined according to the principal of virtual work [1] by taking the numerical derivative of l^{mt} with respect to θ, that is: $ma = \partial l^{mt}/\partial\theta$, and then fitting a fifth-order polynomial to the resulting data.

Results. The real-time images conveyed the complex path of the rectus femoris muscle as it wraps around the anterior portion of the distal femur (Fig. 1-A). The peak moment arm for the example subject (female; height 160 cm; age 30 yrs) was 3.5cm (Fig. 1D). Moment arms estimates compare well with the range of moment arms published by Buford et al. [2]. We are therefore confident in the moment arms measured using this method.

Discussion. We present initial results from a powerful and fast new method for measuring muscle moment arms *in vivo*. Further optimization in the method will include synchronizing multiple slices to acquire three-dimensional muscle and bone motion. Future applications for the method include characterizing moment arms under various loading conditions and studying various other muscles that have complex muscle paths. Moreover, this technique can be used to characterize moment arms in persons with musculoskeletal deformities.

[1] An et al. *J Biomech Eng*, 1984.
[2] Buford et al. *IEEE Trans Rehab Eng*, 5, 367-379, 1997.
[3] Fukanaga et al. *J Biomech*, 3(2):215-8, 2000.

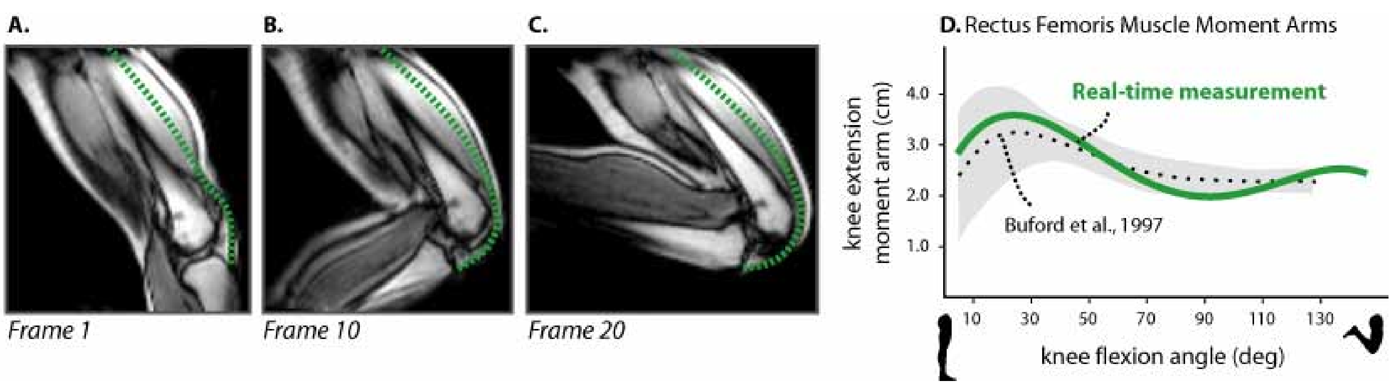

Figure 1. Real-time images (A-C) and knee extension moment arms (D) determined from the real-time images. Green dashed lines in A-C indicate the muscle-tendon length measurement. Knee joint angles were also measured for each frame, and moment arms were calculated through the range of motion. The moment arms are compared with Buford et al., 1997 [2] (dotted lines correspond to the average values from 15 cadaveric specimens; shaded regions correspond to +/- one standard deviation).