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A non-invasive, 3D, dynamic MRI method for measuring muscle moment arms in vivo: Demonstration in the human ankle joint and Achilles tendon

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A B S T R A C T

Muscle moment arms are used widely in biomechanical analyses. Often they are measured in 2D or at a series of static joint positions. In the present study we demonstrate a simple MRI method for measuring muscle moment arms dynamically in 3D from a single range-of-motion cycle. We demonstrate this method in the Achilles tendon for comparison with other methods, and validate the method using a custom apparatus. The method involves registration of high-resolution joint geometry from MRI scans of the stationary joint with low-resolution geometries from ultrafast MRI scans of the slowly moving joint. Tibio-talar helical axes and 3D Achilles tendon moment arms were calculated throughout passive rotation for 10 adult subjects, and compared with recently published data. A simple validation was conducted by comparing MRI measurements with direct physical measurements made on a phantom. The moment arms measured using our method and those of others were similar and there was good agreement between physical measurements (mean 41.0 mm) and MRI measurements (mean 39.5 mm) made on the phantom. This new method can accurately measure muscle moment arms from a single range-of-motion cycle without the need to control rotation rate or gate the scanning. Supplementary data includes custom software to assist implementation.

1. Introduction

Muscle moment arms are used widely in biomechanics to relate joint torques and muscle forces, and to estimate changes in muscle length that accompany changes in joint angle. Some examples include the use of muscle moment arms to determine changes in the length of muscles of patients with muscle contractures [1], assessment of changes in muscle stiffness from joint torque measurements [2,3], or development of subject-specific musculoskeletal models [4,5]. These are applications that often involve dynamic joint motion, so ideally the methods used to measure muscle moment arms for dynamic applications would be non-invasive, simple, and obtained from a moving joint. The measurement should be of the true 3D length of the moment arm [6], not the length of the moment arm projected onto an anatomical plane, and it should be given as a continuous function of joint angle, not just at one angle or a small number of discrete joint angles. In some settings (e.g. clinical) it may be desirable for the method to be quick and involve as little joint movement as possible.

Muscle moment arms can be determined in two ways. The 'geometric method' involves measuring the distance from the joint axis to the muscle-tendon line-of-action whereas the 'tendon excursion method' involves determining the ratio of tendon excursion to joint rotation [7]. Imaging technologies can be used to determine the location of the joint axis and muscle-tendon line-of-action.

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The simplest methods for geometric measurement of muscle moment arms capture anatomical images of the joint and muscle-tendon unit in a single plane at a few static joint positions. The images are used to calculate two-dimensional centres of rotation between consecutive joint positions, and to measure the distance from each centre of rotation to the muscle-tendon line-of-action in the same plane [8]. A study by Rugg et al. demonstrated that Achilles tendon moment arms were only minimally affected when using a fixed versus moving centre of rotation [9]; however, that study was performed using two-dimensional MRI scanning of the ankle joint in sequential stationary postures. Two-dimensional methods may be subject to errors in locating the joint axis because most joints do not behave as planar mechanisms. More recent studies have used three-dimensional imaging techniques to determine the 3D distance between the joint axis and the muscle-tendon line-of-action [6,10–12], and a recent study by Hashizume et al. [6], demonstrated that measurements from 2D MRI scans significantly overestimate the Achilles tendon moment arm compared to measurements from 3D MRI scans. While three-dimensional, these methods still involve static positioning of the joint at a small number of joint angles. The interest is often in the moment arm under dynamic conditions (e.g. for dynamic musculoskeletal models or joint dynamometry), and joint axes have been demonstrated to behave differently under static and dynamic conditions [13].

A major technical advance was the use of cine phase-contrast MRI to obtain non-invasive geometric measures of joint helical axes and muscle moment arms in three dimensions under dynamic conditions [14,15]. The technique uses cyclical joint rotation and analysis of velocity encoded data to define the joint helical axes and calculate muscle moment arms. To the best of our knowledge that is the only previously published non-invasive geometric technique that has been used to measure three-dimensional muscle moment arms under dynamic conditions (at the knee and ankle), and therefore as a near-continuous function of joint angle.

Our objective was to develop and validate a non-invasive method to measure 3D dynamic muscle moment arms that: (1) could be performed using a single joint rotation cycle; (2) has the potential to be used under either active or passive (relaxed) muscle conditions; and (3) does not require control of joint angular velocity or MRI gating.

2. Materials and methods

2.1. Participants

Participants were 10 healthy adults (5 men, 5 women) with a mean age of 29 years (range 22–48 years). Healthy subjects were used for ease of comparison with other published methods. All subjects gave written informed consent to participate. The methods were approved by the Human Research Ethics Committee of the University of New South Wales.

2.2. MRI scanning

Participants were positioned prone in a 3T MRI scanner (Phillips Achieva, Netherlands) with flexible surface coils strapped to the ankle, and with the foot strapped to a custom jig that allowed an operator to passively rotate the ankle from outside the scanner bore. The thigh and hips were supported on cushions with the knee flexed between 5° and 10°. The relaxed ankle was passively rotated by one of the investigators.

A method for tracking joint position [16,17] was extended to the calculation of muscle moment arms. A key feature of the method is optimised registration (co-localisation) of high-resolution static bone geometries with lower-resolution bone geometries captured using an ultrafast scanning method while the joint is slowly rotated. The coordinates describing the location of the registered geometries were used to reconstruct 3D dynamic joint rotation.

The scanning protocol included one high-resolution 'static' scan of the stationary joint (3D T1-weighted FSE, 4.7 min, flip angle 90°, matrix 320 × 320, FOV 160 mm × 160 mm, TR/TE = 355.76/16.68 ms, slice thickness 1 mm) (Fig. 1A) followed by a series of low-resolution 'dynamic' scans obtained while the joint was slowly rotated through its range of motion (ultrafast (turbo) gradient echo, 104 s, 40 dynamics (phases), 8 slices (sagittal), flip angle 10°, matrix 320 × 320, FOV 320 mm × 320 mm, TR/TE = 2.731/1.34 ms, slice thickness 4 mm, slice gap 0.4–3.0 mm, depending on joint size) (Fig. 1B and C). The orientation of and gap between the 8 slices across the joint should be subject- and joint-specific; here the slice orientation was aligned with the plane of the Achilles tendon from a coronal view, and the slice gap was adjusted to capture 4–5 slices across the Achilles tendon (see Section 4). The current study used 40 repetitions or time-phases for 1–2 cycles of joint rotation (i.e., 10–20 frames each of joint flexion and extension), which required a total scan time of less than 2 min. The mean joint rotation rate for 10 subjects was 1°/s. We aimed to maintain a consistent passive rotation rate for each subject but did not specifically match rotation rates between subjects (standard deviation was 0.6°/s). Dynamic scan data were displayed as 8 'movies' of the rotating joint, one for each of the 8 slices (see Supplementary material). The ankle angle for each phase was measured from a single mid-sagittal slice as the angle between the anterior surface of the tibia and the base of the heel on the footplate.

Fig. 1. Representative static and dynamic images: (A) one mid-sagittal image from the high-resolution static scan. (B) One mid-sagittal image from the low-resolution dynamic scan during plantarflexion and (C) dorsiflexion.