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Estimation of musculotendon kinematics under controlled tendon indentation

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ABSTRACT

The effects of tendon indentation on musculotendon unit mechanics have been left largely unexplored. Tendon indentation is however routinely used in the tendon reflex exam to diagnose the state of reflex pathways. Because muscle mechanoreceptors are sensitive to mechanical changes of the musculotendon unit, this gap in knowledge could potentially impact our understanding of these neurological exams.

Accordingly, we have used ultrasound (US) imaging to compare the effects of tendon indentation with the effects angular rotation of the elbow in six neurologically intact individuals. We used sagittal ultrasound movies of the biceps brachii to compare length changes induced by each of these perturbations. Length changes were quantified using a pixel-tracking protocol.

Our results show that a 20 mm indentation of the distal tendon is broadly equivalent to a 15° elbow rotation. We also show that within the imaging window the strain differences between the two stretching protocols are statistically insignificant. Finally, we show that there exists a significant linear relationship between the two stretching techniques and that this relationship spans a large rotational angle to indentation depth.

We have used a novel tendon probe to administer controlled tendon indentations as a way to characterize musculotendon kinematics. Using this probe, we confirm that tendon indentation can be physiologically equated with joint rotation, and can thus be used as an input for muscle stretching protocols. Furthermore, this is potentially a simpler and more practical alternative to externally imposed angular joint motion.

1. Introduction

In the course of the standard neurological exam, a clinician records myotatic reflexes by stretching muscles in two ways: by rotating a joint, or by tapping a tendon with a reflex hammer. Both techniques stretch the muscle, and both stimulate the muscle receptors that trigger the reflex responses. To the best of our knowledge, however, the kinematic relationship between each stretching paradigm has not been explored. Furthermore, the muscle kinematics recorded in response to tendon indentation alone are also largely unexplored, potentially hindering our basic understanding of stretch reflex mechanisms.

We now know that the tendon reflex response is dependent on several controllable factors, such as the amplitude of the tendon tap and the frequency with which the tap is delivered (Voerman et al., 2005). More recently, we have shown that controlling the depth of tendon indentation prior to the tap also elicits reflex patterns resembling ones found for progressive whole limb rotation (Chardon et al., 2014). Accordingly, there is potentially a strong correlation between the parameters impacting the tendon reflex and the kinematics of the muscle prior, during and after the tendon tap. However, we do not currently know how much stretch is delivered by tendon indentation, and how this stretch compares with that generated by a standard angular joint rotation.

Presently, global musculotendon unit movements are routinely studied using ultrasound (US) medical imaging, because of its unparalleled ability to record tissue motion in vivo. However, the majority of the studies stretch a muscle using controlled joint rotation (Blemker et al., 2007). In contrast, tissue indentation protocols

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are often used to assess local muscle mechanics. When applied in cadaveric specimens (Palevski et al., 2006; Van Loocke et al., 2006, 2008) or on muscle belly (Iivarinen et al., 2011; Leonard et al., 2001; Uchiyama et al., 2000), the indenter is used to record compression force and the associated tissue displacement, recorded either from the indenter motion, or from imaging techniques (Moerman et al., 2011; Zheng and Mak, 1996). While extremely important, these indentation paradigms can only provide insights about local rather than global musculotendon unit mechanics. There is also no way currently to integrate findings drawn from joint rotation with those derived from tissue indentation.

In this study, we explore and compare whole muscle kinematics of the biceps brachii (BIC) muscle under tendon indentation and during a standard joint rotation at the elbow. We plan to use US imaging as a tool to record internal muscle deformation. We further seek to demonstrate whether muscle length changes during tendon indentation can be equated with joint rotation, and whether such tendon indentation produces physiologically meaningful changes in muscle length. We chose the BIC as our model system because it has an easily accessible distal tendon. For our muscle kinematics measures, we used B-mode US imaging.

2. Method

2.1. Participants

Six neurologically intact individuals, of age 31 ± 5.2 years, were recruited and their dominant side was tested once. All participants gave informed consent via protocols approved by the Institutional Review Board under the Office for the Protection of Human Subjects at Northwestern University.

2.2. Experimental setup

Each subject was seated in a Biodex chair and the forearm was braced to a custom arm rotation device (Fig. 1A). The subject's position was adjusted such that shoulder-abduction was 10°, shoulder-flexion 10°, elbow-flexion was 120° and forearm-supination was 0°. The arm brace was also adjusted such that the axis of rotation of the elbow was collinear to the axis of rotation of the rotation device.

The US probe and tendon tapper were placed near to the distal muscle–tendon junction of the BIC, identified using US and marked by tape (Fig. 1). Specifically, using the 8 adjustments of a custom US probe holder, we placed the probe orthogonal to the shorter axis of the BIC (sagittal-plane), closest to the distal tendon at 1 cm distance. We then used the rotational adjustments to increase the reflectivity of the tissue below and further ensured that the muscle could be tracked throughout the range of angles. We then placed the tendon tapper such that its tip indented the distal end of the BIC muscle at an angle of attack 90° to the humerus.

Each protocol had 5 trials. In a single rotation trial, the forearm was extended at a PID controlled velocity (0.08 rad/s) from 120° elbow flexion to 150° and then rotated back after a 5 s pause. For a single indentation trial, the tendon tapper was lowered onto the tendon at a PID controlled velocity (5 mm/s) from skin (0 mm) to a distance of 20 mm and was then returned after a 5 s pause. Subjects were instructed to keep their muscles quiescent during the trials.

The US movies were collected using a GE-Logiq9-R6.0.5 and a GE-M12L probe set at a frequency of 14 MHz, gain of 63 dB at a recording depth of 30 mm and width of 50 mm. For each rotation and tendon indentation cycle, we stored for later analysis (533 × 436) grayscale DICOM movies. We used Matlab-xPC-2011a to collect, to control the trajectories of motors and to synchronize the motors with the US machine.

2.3. Data analysis

2.3.1. Motion tracking – X, Y and Total Distance

The motion or kinematics of the BIC for each stretching protocol was estimated by tracking features within the US images by eye. Prior to tracking, two feature of interest (FOIs) were identified along the main axis of the muscle along the aponeurosis (dashed middle white line in Fig. 2A) at an ultrasound image width location of 5 mm and 35 mm. In order to qualify, the FOI had to be present in both protocols and had to remain trackable for all movie frames ($f = 1,2, \ldots, m$).

Given the FOIs, the US movies were analyzed by hand by two different raters using a custom script. Each rater was given the location of the FOI only for the initial frame. The first rater reanalyzed the US movies at a later date to test within-rater repeatability.

Subsequent to tracking, the raw pixel vectors [X_f,Y_f] of the FOI (Fig. 2A) were offset from their initial positions and converted into metric units. Given the protocol, the [X_f,Y_f] pairs were synchronized

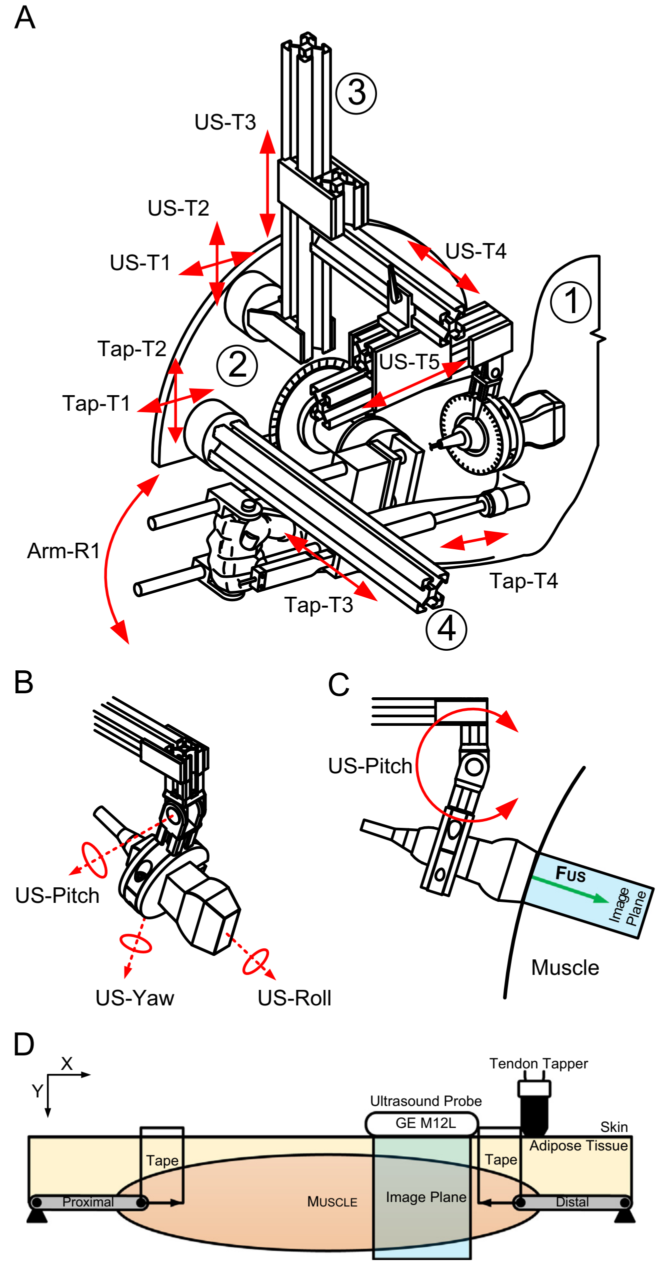

Fig. 1. Experimental setup. (A) Schematic of the whole experimental setup. There are four parts to the schematic. ① The cutout of the subject's arm. ② The rotational motor to which is attached the brace for the lower arm. ③ The ultrasound probe holder with the probe. ④ The tendon tapper holder with the tendon tapper. (B) Close up of the schematic of the end effector of the ultrasound probe holder. The design allows the probe to be adjusted in the roll, pitch and yaw to optimize for the quality of the ultrasound image. (C) The interaction force – FUS – with the skin and muscle. (D) Schematic of the placement of the different probes relative to the biceps brachii. From left to right, the tendon tapper is set above the tendon–muscle junction. A piece of clear tape from the tendon tapper, acts as the reference for the ultrasound probe.