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Influence of forearm orientation on biceps brachii tendon mechanics and elbow flexor force steadiness

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Achilles tendon mechanics influence plantar flexion force steadiness (FS) and balance. In the upper limb, elbow flexor FS is greater in supinated and neutral forearm orientations compared to pronated, with contributions of tendon mechanics remaining unknown in position-dependent FS. This study investigated whether distal biceps brachii (BB) tendon mechanics across supinated, neutral and pronated forearm orientations influence position-dependent FS of the elbow flexors. Eleven males (23 ± 3 years) performed submaximal isometric elbow flexion tasks at low (5, 10% maximal voluntary contraction (MVC)) and high (25, 50, 75% MVC) force levels in supinated, neutral and pronated forearm orientations. Distal BB tendon elongation and CSA were recorded on ultrasound to calculate mechanics of tendon stress, strain and stiffness. Relationships between FS, calculated as coefficient of variation (CV) of force, and tendon mechanics were evaluated with multiple regressions. Supinated and neutral were ~50% stronger and ~60% steadier than pronated ($p < 0.05$). Tendon stress was ~52% greater in supinated and neutral compared to pronated, tendon strain was ~36% greater in neutral than pronated ($p < 0.05$), while tendon stiffness (267.4 ± 78.9 N/mm) did not differ across orientations ($p > 0.05$). At low forces, CV of force was predicted by MVC (r^2: 0.52) in supinated, and MVC and stress in neutral and pronated (r^2: 0.65–0.81). At high force levels, CV of force was predicted by MVC and stress in supinated (r^2: 0.49), and MVC in neutral (r^2: 0.53). Absolute strength and tendon mechanics influence the ability of the BB tendon to distribute forces, and thus are key factors in position-dependent FS.

1. Introduction

Tendons exhibit viscoelastic properties allowing them to deform in response to an applied force and return to their resting state following that force. As tendons provide the link between muscle and bone, their viscoelastic nature influences how force is transferred from muscle to bone; however, the tendon's ability to modulate this force output is not well understood. Modulation of force output is key for force control tasks such as force steadiness (FS); the ability to maintain force around a given target force level (Brown et al., 2010; Enoka et al., 2003; Pereira et al., 2015). The tendon's ability to lengthen and experience strain with applied force depends on its inherent stiffness (Onambélé et al., 2007a). As the tendon lengthens in response to the applied force cross-sectional area (CSA) is reduced, placing greater stress on the tendon with increased force (Obst et al., 2014; Smart et al., 2017). These changes in the tendon are likely to contribute to precise control of force, such as that required for elbow flexor FS.

Isometric elbow flexor FS is position-dependent with the supinated and neutral forearm orientations being steadier than the pronated orientation (Brown et al., 2010). Force steadiness is also influenced by strength, with increased strength leading to increased FS (Brown et al., 2010; Enoka et al., 2003; Smart et al., 2018). Based on previous findings of greater strength and FS in supinated and neutral orientations compared to pronated (Brown et al., 2010) and the influence of strength on tendon mechanics (Folland and Williams, 2007), it is likely that chronic loading or unloading would alter tendon mechanics, and contribute to position-dependent elbow flexor FS. Moreoever, as the radius articulates overtop of the ulna as the forearm rotates between supinated, neutral and pronated orientations, the resting length of the distal biceps brachii (BB) tendon would likely be affected. These potential differences in tendon due to forearm rotation as well as strength would influence force transfer from muscle to bone, and contribute to position-dependent FS of the elbow flexors.

Previous studies examining the role of tendon mechanics in force control have focused on the contribution of Achilles tendon stiffness to standing balance (Onambélé et al., 2007b, 2006), and the normalized stiffness measure of Young's Modulus to isometric force control (Johannsson et al., 2015). These studies indicate that

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a stiffer tendon improved balance and FS. With strength being a primary contributor to tendon mechanics (Folland and Williams, 2007) and FS (Brown et al., 2010; Enoka et al., 2003; Smart et al., 2018), and the supinated and neutral forearm orientations being both stronger and steadier compared to pronated (Brown et al., 2010), it is likely that tendon stiffness is greater and strain is less in supinated and neutral, contributing to these orientations being steadier than pronated. The greater strength in supinated and neutral will likely culminate in higher levels of tendon stress for these orientations, which may also contribute to increases in FS. These potential orientation differences in distal BB tendon mechanics would further the understanding of mechanisms that contribute to position-dependent elbow flexor FS (Brown et al., 2010). The purpose of this study was to quantify mechanics of the distal BB tendon across supinated, neutral and pronated forearm orientations, and determine the influence of these tendon mechanics on position-dependent FS of the elbow flexors. We hypothesized that supinated and neutral would have lower levels of strain compared to the pronated orientation, but higher levels of tendon stress and stiffness, contributing to the position-dependency of elbow flexor FS.

2. Methods

Eleven right-hand dominant males (23 ± 3 yrs, 175.6 ± 8.2 cm, 72.9 ± 7.5 kg) volunteered to participate in the present study. Each participant visited the lab for three experimental sessions separated by ~48 h. Exclusion criteria were: (1) active tendinopathy, (2) systemic disease affecting collagenous tissue, (3) history of injury or orthopaedic surgery to the right arm or shoulder in the prior 6 months, (4) high levels of upper-body strength training, (5) history of training in fine motor tasks (i.e. musicians), (6) nerve damage to right arm. Ethics approval was obtained from the University of British Columbia Behavioural Research Ethics Board, and informed written consent was obtained from participants prior to participating.

2.1. Experimental setup

Participants were seated in a custom-built dynamometer chair with the knees and hips positioned at 90°, the elbow placed in 110° of flexion (180° being full extension) resting on a padded support, and the shoulder in 15° of forward flexion. The manipulandum was grasped with the dominant hand in supinated (palm up, 90° externally rotated from neutral), neutral (palm vertical, 0°) and pronated (palm down, 90° internally rotated from neutral) orientations, and elbow flexion force was recorded using a MLP-150 linearly calibrated force transducer (68 kg, 266 V sensitivity) (Transducer Techniques, Temecula, CA, USA) located below the wrist. The force signal was displayed in real-time on a 52 cm monitor located 1-meter in front of the participant and adjusted for the middle of the monitor to be at eye-level. Force signals were amplified (100×), sampled at 2381 Hz using a 16-bit plus analog to digital converter (Cambridge Electronic Design (CED), Cambridge, England), and stored for offline analysis (Spike 2 V7, CED, Cambridge, England). During the submaximal tracking tasks, the ultrasound probe was placed in a custom probe holder and secured to the arm either in a longitudinal plane to visualize the distal BB muscle-tendon junction (MTJ) (Fig. 1), or a transverse plane to view the distal BB tendon in cross-section.

Anatomical measures were performed for supinated, neutral and pronated forearm orientations. BB resting muscle length and CSA, as well as resting distal BB tendon length were recorded using an ML6-15 B-mode ultrasound probe (GE LOGIQ E9; General Electric, Fairfield, CT, USA) with the LOGIQView® function, allowing panoramic scans of the structure of interest. Muscle length was recorded from the proximal to distal MTJs of the BB, and muscle CSA was recorded at the midpoint of the muscle belly. Distal tendon length was measured from the distal BB MTJ to its insertion onto the radial tuberosity, and tendon CSA was measured at the point of largest area. Lever arm length was recorded from the lateral condyle of the humerus to the force transducer and the BB moment arm length was obtained as the perpendicular distance from the line of the distal BB tendon to the radio-humeral articulation.

2.2. Protocol

2.2.1. Testing session 1

Following resting anatomical measures participants performed 2–3 five-second MVCs. This was repeated for all three forearm orientations in a randomized order. Participants were given 2–3 min rest between contractions to prevent fatigue.

2.2.2. Testing sessions 2 and 3

MVC was re-established for each forearm orientation by having participants match their previous days' MVC within 5%. Participants then performed isometric tracking tasks at 5, 10, 25, 50 and 75% MVC in the supinated, neutral and pronated orientations. The task involved a 5-second resting state, a 3-second ramp to the target force, a 10-second plateau at the target force level, and a 3-second de-ramp returning to baseline. The target forces were

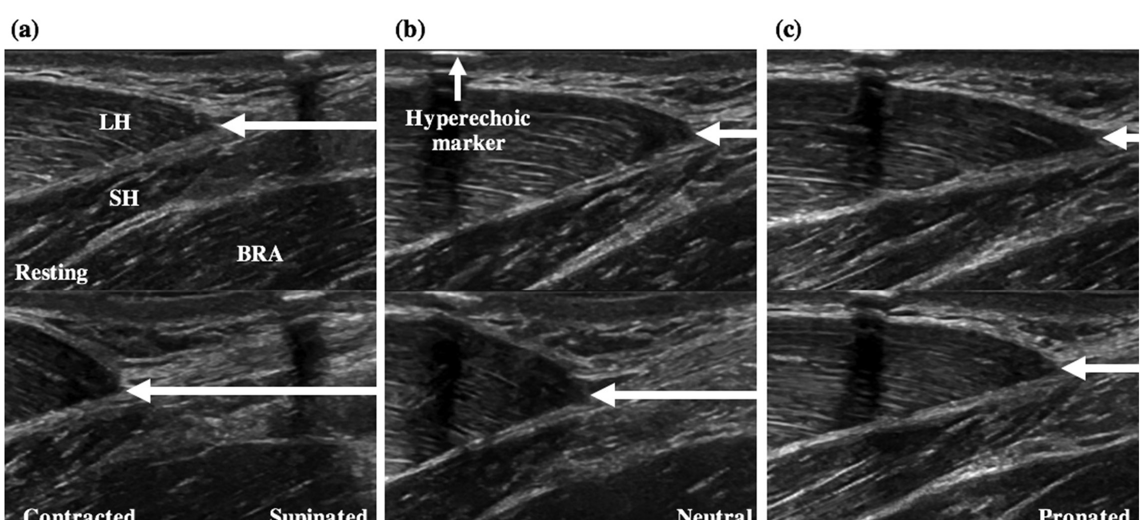

Fig. 1. Tendon elongation at 50% MVC across supinated (a), neutral (b) and pronated (c) forearm orientations. LH, long head biceps brachii; SH, short head biceps brachii; BRA, brachialis.

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