The OpenArm Project: Exploring Deformation as a Measure of Muscle Force

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Introduction

While many musculoskeletal simulation frameworks rely on estimates of muscle force [1], there exists no noninvasive, in vivo method of measuring the force exerted by individual muscles. Instead, forces are estimated based on motion-specific assumptions and/or noisy measures of neural activation. A direct, accurate measure of muscle force would enable improved understanding of dexterity, better quantification of pathology, and safer, more expressive assistive device control. We propose measuring muscle force via *muscle deformation*, a signal that is intrinsically coupled to force production: as muscles shorten and widen during the cross-bridge cycle, tendons lengthen and force increases. In this work, we present *a)* evidence that this deformation is observable during voluntary exertion and (when correctly parameterized) is correlated with joint torque; *b)* preliminary findings on useful signals for force inference; and *c)* the OpenArm project,[1] an open-source collection of data and analysis code to enable study of the force–deformation relationship by the wider research community.

Methods

While deformation is readily observable via 2D ultrasound in the movement of each muscle's surrounding fascia, the observed signal changes substantially based on an individual's morphology, the geometry induced by their joints' kinematic configuration, contact dynamics with other tissue, and sensor location. To enable analysis under this complexity, we developed two exploratory data sets: first, a set of full 3D reconstructions of elbow flexor muscle volumes under varied (static) loading conditions [2, 4], and second, time series data of 2D brachioradialis deformation under isometric time-varying loads and alongside sEMG values [3]. Both sets were collected using ultrasound under multiple elbow angles and for multiple subjects. These data were then analyzed geometrically to establish the relationship between elbow force and various parameterizations of the deformation signal.

Results and Discussion

Example data is shown in Fig. 1. As reflected in the 3D exemplar, the overall shape of the elbow flexors is irregular; however, when cross-sectional area (*CSA*) is measured from a certain range of locations along the biceps brachii, this *CSA* value reliably increases with force exertion, a relationship that generalizes across elbow angles (but varies in magnitude) [2]. These observations confirm the feasibility of measuring force-associated deformation signals and affirm the importance of considering both kinematic configuration and sensor location during their analysis.

Similarly, the exemplar time series data in Fig. 1 — collected from a location along the arm informed by our 3D analyses — show that this static correlation between joint force and muscle *CSA* (and two other deformation measures) extends to dynamic isometric contractions [3]. While these correlations are reliably strong across subjects and most elbow angles, the measure that is most correlated — and even the sign of that correlation — varies by subject. These results confirm that the force-associated deformation studied in our static analyses can be observed (and tracked [3]) over time from a single ultrasound scan; they also highlight the importance of accounting for individuals' morphological variation.

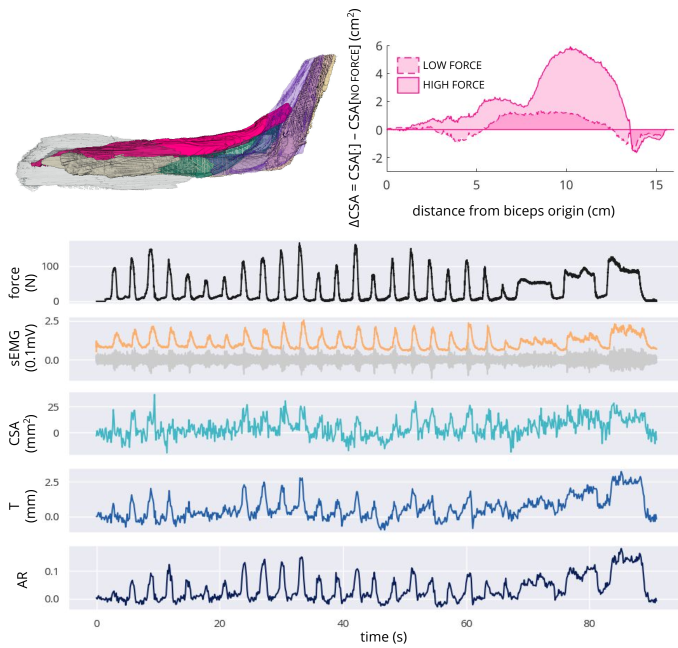

Figure 1: *Top:* Example 3D reconstruction of the elbow flexors (*left*) alongside biceps cross-sectional area (*CSA*) changes under force loading (*right*) [2]. *Bottom:* Time series force and sEMG data alongside three measures of brachioradialis deformation (*CSA*, thickness *T*, and aspect ratio *AR*) during pulsed and sustained isometric contractions [3].

Significance

Our results constitute quantitative evidence that deformation signals are both observable and correlated with joint force under isometric conditions; ultimately, we aim to expand this predictive power to individual muscle forces during natural movement. Identifying good signals for such models will require extensive exploratory data analysis, but will open up new avenues of research in biomechanics, neuroscience, robotics, ergonomics, and even animation. Our system identification efforts use the SimTK OpenArm platform, which contains all data and analyses described here and which we hope will inspire novel collaboration across these domains.

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[1] https://simtk.org/projects/openarm