MOMENT ARM MEASUREMENT TO VALIDATE A CLOSED-LOOP FEEDBACK-CONTROLLED ELBOW JOINT SIMULATOR

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INTRODUCTION

To have a complete understanding of a joint's function, one must understand both the anatomic parameters and how the brain controls the joint's actuation. Accurate measurements of anatomical parameters are critical to nonlinear biomechanical modeling, to control, and to a clinical understanding of orthopaedic reconstruction. Likewise, the study of neuromuscular control contributes to our understanding of joint structure and function. Towards the goals of understanding and improving human elbow joint control, a physiologic elbow joint simulator which operates completely under closed-loop control has been constructed in our laboratory. The closed-loop force control also permits measurement of moment arms in cadaveric elbow specimens. We hypothesized that this approach is valid in the sense that it yields comparable moment arms to previously-reported values (cf. Magnusen, 2002.)

METHODS

The hardware design has been previously developed and described (Magnusen, 2002.) Briefly, four servoelectric actuators (BE series, Parker-Hannifin, Rohnert Park, CA) are attached via high-tension cable to each of the major muscles that act across the elbow joint: the *biceps brachii*, *triceps brachii*, *brachialis* and *pronator teres*. Custom pulleys preserved the physiologic lines of action of these muscles. In-line load cells (Model 31, Honeywell Sensotec, Columbus, OH) monitored muscle forces which were used as feedback to the ACR8020 (Parker-Hannifin, Rohnert Park, CA) controller. For this study, a proportional only controller maintained constant force on each actuator. Custom mounts held potentiometers aligned with both the flexion/extension (f/e) and pronation/supination (p/s) axis (P1401a, Novotechnik, Southborough, MA.)

An axis finder, modeled after Hollister *et al.* (1992), was used to ensure proper potentiometer alignment. High-tension cable (80lb, Stren, Spirit Lake, IA) was sutured to the tendons of the fresh-frozen cadaveric elbow specimen with Krackow whip stitches. Knots in the cable were reinforced with cyanoacrylate adhesive. Minimal tissue was excised from the specimen to preserve its inertial properties.

Once secured to the simulator's frame, each tendon was loaded to a minimum of 22.24 N. Equal forces in all muscles were not possible due muscle redundancy and low static friction in the system. With the cylinders operating in force control to maintain constant tension in the lines, the elbow was manually actuated. Six cases were studied: f/e motion with the p/s angle of 1) neutral, 2) fully pronated, 3) fully supinated, and p/s motion with the f/e angles held constant at 4) 30°, 5) 60°, and 6) 90°.

To maintain constant force, the cylinders moved as prescribed by the controller, thus cylinder travel was equivalent to tendon excursion. Data were recorded at 20 Hz. A minimum of three motion cycles of each type was collected.

Subsequent analysis was completed using MATLAB (The MathWorks, Natick, MA, USA.) Fourth-order polynomial curves were fit to both the potentiometer (joint angle, θ) and cylinder travel (tendon excursion, r.) These curves were differentiated and the moment arms were calculated using the following equation:

$$M.\ A. = dr/d\theta \quad (1)$$

RESULTS AND DISCUSSION

The computed moment arms for the *brachialis* (Figure 1) compare well with previously-reported results and our design intent (Magnusen, 2002; Kuxhaus 2005.) As expected, the f/e moment arms do not vary much with changes in p/s angle. The moment arms in flexion differ slightly from those in extension due to controller lag and movement direction. A PI controller and correction for friction may reduce this effect. Figure 2 also compares well with established moment arm values (Bremer *et al.*, 2006) and shows that for the *biceps brachii*, the p/s moment arms vary systematically with f/e angle. Slight changes (<6°) in the f/e angle during measurement caused the variability in the f/e=90° case. The minimum R-squared value for all fitted curves is >0.99.

SUMMARY

The measured muscle moment arms agree with established values. This validates one aspect of the elbow simulator's design and illustrates the feasibility of this new technique. Future work will refine this technique for use in a system identification process and model-reference control scheme.

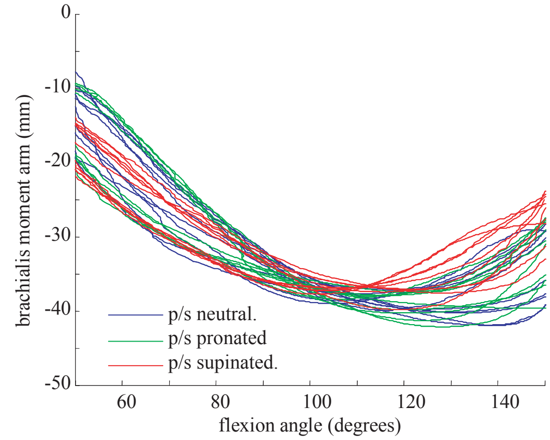

Figure 1: Brachialis f/e moment arms at varying p/s angles.

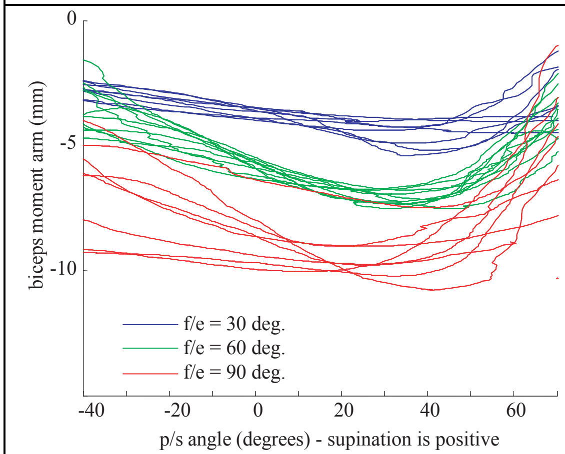

Figure 2: Biceps p/s moment arms at varying f/e angles.

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