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Short communication

Dependence of elbow joint stiffness measurements on speed, angle, and muscle contraction level

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ABSTRACT

Elbow joint stiffness is critical to positioning the hand. Abnormal elbow joint stiffness may affect a person′s ability to participate in activities of daily living. In this work, elbow joint stiffness was measured in ten healthy young adults with a device adapted from one previously used to measure stiffness in other joints. Measurements of elbow stiffness involved applying a constant-velocity rotational movement to the elbow and measuring the resultant displacement, torque, and acceleration. Elbow stiffness was then computed using a previously-established model for joint stiffness. Measurements were made at two unique elbow joint angles, two speeds, and two forearm muscle contraction levels. The results indicate that the elbow joint stiffness is significantly affected by both rotational speed and forearm muscle contraction level.

1. Introduction

The elbow joint plays a pivotal role in positioning of the hand and therefore to activities of daily living (ADLs). While a range of from 30° to 130° of flexion (Morrey et al., 1981) is necessary to perform ADLs, elbow stiffness logically also contributes. An elbow that is too stiff or not stiff enough may result in sharp, jumpy, or uncontrolled motion, may result in spasticity (Park et al., 2004) or require clinical treatment (Gallay et al., 1993).

Rotational joint stiffness, a measure of joint compliance, describes the relationship between a torque applied to a joint and its rotational deformation (Flaherty et al., 1995; Kearney et al., 1997; Robinson et al., 1994, 1998; Tai et al., 1999; Tai and Robinson, 1999). Previous research used linear models to describe joint stiffness of the ankle (Gottlieb and Agarwal, 1978; Kearney and Hunter, 1982; Kearney et al., 1997), wrist (Lakie et al., 1984), and elbow (Lacquaniti et al., 1982). Given that the elbow could be a nonlinear biological system, elbow stiffness should vary with movement speed, joint position, and muscle contraction level, as the ankle joint does (Agarwal and Gottlieb, 1971). Elbow stiffness does vary with gender, triceps co-contraction level, and initial angle when near extreme extension (Lee and Ashton-Miller, 2011). While it has been previously quantified, (Latash and Gottlieb, 1991; Lee and Ashton-Miller, 2011; Lin et al., 2005, 2003; Zatsiorsky, 2002) a description of elbow stiffness near the midpoint of the elbow′s operating range is absent. Such a quantification could be applied to increase the fidelity of musculoskeletal models, or improve rehabilitation protocols, especially those to address elbow spasticity. Stiffness certainly varies with contraction level, and could also with rotational speed. It could also be affected by neuromuscular disorders or musculoskeletal injury. Thus, having a way to measure elbow stiffness in intact unimpaired arms could indicate how well individuals could perform routine ADLs. An ancillary purpose of this study was to quantify the effects of initial position (joint angle), movement speed, and muscle contraction on elbow stiffness in healthy young subjects. Our hypothesis was that describing elbow joint mechanics at mid-range positions would not require a damping term.

2. Methods

Elbow joint stiffness was measured in ten healthy young adults (age: 24.4 ± 2.7 years; 5 female) who self-reported right-hand dominance. Subjects were excluded if they could not sit comfortably for two hours, or self-reported a history of any upper extremity trauma or disorder, including: peripheral neuropathies; neural or muscular disorders including muscle spasms; or non-traumatic arthritis in any joint. A goniometer was used to verify that all subject had a range of motion of at least 50–180° (included elbow joint angle.) All subjects gave informed consent under a protocol approved by the Institutional Review Board of Clarkson University.

After viewing a demonstration of the measurement procedure, each subject′s maximum grip force (MVC) was measured three times with a dynamometer (Model 12-0291, Baseline, White Plains, NY). Subjects then sat next to the stiffness tester (Fig. 1), as modified from Tai and Robinson (1999) and adjusted the chair′s position so that their forearm rested on the support and the shoulder was abducted. The forearm was coupled to the stiffness tester in a slightly pronated position, such that

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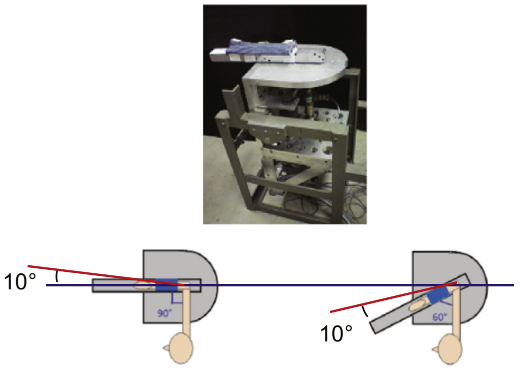

Fig. 1. Photo of stiffness tester (top), and sketches to illustrate motions performed. For each motion, the elbow was extended 10° beyond the initial angle, then flexed back at the same speed.

a line connecting the ulnar and radial styloids of the wrist was approximately parallel to the floor, in the plane of flexion/extension movement. An axis finder modeled after Hollister et al. (1992) was used to align the axis of rotation of the elbow with that of the stiffness tester. A cloth sleeve around the subject's forearm with Velcro closures coupled the forearm to the stiffness tester and permitted quick disconnection at any time with minimal force. Additional safety controls were implemented at the hardware (hard stops) and software (programmed stops) levels, including a "kill-all" power button within reach of the researcher.

The torque motor (Model JR24M42CH, PMI, Waltham, MA) was controlled via proportional-integral-derivative (PID) feedback control, and data collection was performed at 500 Hz via custom LabVIEW code (National Instruments, Austin, TX). A rotational movement of approximately 10° (extension) was applied to the elbow joint at nominally fast and slow speeds, as described below. The elbow was held at the extended position for two seconds, and then returned to the original position at the same speed (Fig. 1). The motor's torque was measured via a rotary torque transducer (Model 2121-1K, LeBow Products Inc., Troy, MI), displacement by a rotary transducer (Model 0603-0001, Transtek, Ellington, CT) and acceleration by an accelerometer (ADXL001, Analog Devices, Norwood, MA) positioned at the end of the pivot arm, tangential to the rotational movement.

Joint stiffness was then measured three times in each of eight different test conditions (Table 1), spanning all combinations of two initial elbow joint angles within the range of ADLs (60° and 90° included elbow joint angle), two rotational movement speeds ("slow" and "fast", constant speeds as indicated in Table 1), and two muscle contraction conditions (relaxed and 20% MVC, monitored by the dynamometer). A minimum of 30 s rest was required between measurements. All measurement trials were used in analysis.

2.1. Data processing

Custom MATLAB code was used to digitally filter the measurements with a second-order low-pass Butterworth filter with a 100 Hz cutoff frequency. A window of 50 data points from within the constant velocity portion of the move was selected from both the flexion and extension movements of each trial for analysis. This window was selected based on the linearity of the position, torque and displacement data; the 50-point region with the highest coefficient of determination, based on a linear fit, was chosen.

Elbow joint stiffness, K, was then calculated using the following model:

$$T(t) = J\ddot{\theta}(t) + B\dot{\theta}(t) + K\theta(t) + T_0 \tag{1}$$

in which $T(t)$=torque, J=rotational inertia, $\ddot{\theta}$=angular acceleration; B=viscous damping coefficient, $\dot{\theta}(t)$=angular velocity, K=stiffness coefficient, $\theta(t)$=angular displacement, and T_0=constant torque bias (Robinson et al., 1994). If only the constant-velocity portions of the movements are considered, $\ddot{\theta}(t) = 0$, and Eq. (1) becomes

$$T(t) = B\dot{\theta}(t) + K\theta(t) + T_0 \tag{2}$$

which is valid only during constant-velocity portions of the movement, such as the data selected for analysis in this study. To evaluate the contribution of viscous damping to elbow joint stiffness, joint stiffness was computed using both Eq. (2) and the following Eq. (3):

$$T(t) = K\,\theta(t) + T_0 \tag{3}$$

where $\dot{\theta}(t)$ was calculated as the slope of the linear part of the angular displacement signal.

2.2. Statistical analysis

An analysis of variance (ANOVA) was used to test for effects of two speeds, two different muscle contraction conditions, two different initial elbow joint angles, and two motions (extension and flexion) with MATLAB. A p-value of < 0.05 was considered statistically significant.

Table 1
Average velocities used for each test condition. A negative velocity indicates flexion motion.

Test condition	Movement direction	Average velocity °/s (rad/s)
SR90	Extension	15 (0.26)
(Slow, relaxed, 90°)	Flexion	−11 (−0.19)
FR90	Extension	67 (1.17)
(Fast, relaxed, 90°)	Flexion	−45 (−0.79)
SC90	Extension	17 (0.30)
(Slow, contracted, 90°)	Flexion	−12 (−0.21)
FC90	Extension	60 (0.52)
(Fast, contracted, 90°)	Flexion	−46 (−0.80)
SR60	Extension	11 (0.19)
(Slow, relaxed, 60°)	Flexion	−16 (−0.28)
FR60	Extension	43 (0.78)
(fast, relaxed 60°)	Flexion	−66 (−1.18)
SC60	Extension	11 (0.19)
(Slow, contracted, 60°)	Flexion	−20 (−0.35)
FC60	Extension	40 (0.70)
(Fast, contracted, 60°)	Flexion	−57 (−0.99)

3. Results

Stiffness values were not notably different between the two calculation methods. Of the 480 measurement trials analyzed (10 subjects × 8 test conditions × 3 measurements of each × 2 flexion/extension), only eight had a non-zero difference between K as computed using Eqs. (2) and (3). Of those eight trials, the range of differences was small, ranging from −0.3 to +0.13 Nm/rad. The measured elbow joint stiffness values are shown in Fig. 2. For a given initial joint flexion angle, the stiffness values tended to increase with rotational speed, both with and without muscle contraction.

The variation in elbow stiffness is shown in Table 2 (extension) and 3 (flexion), tabulated by subject and test condition. The four-way ANOVA revealed that speed ($p < 0.001$) and muscle contraction ($p = 0.01$) significantly affected joint stiffness. This indicates that, for this sample of healthy young adults, movement direction and initial joint angle did not significantly affect elbow joint stiffness in the mid-range of elbow motion. The results may be different if initial angles are closer to the extremes of elbow motion were tested.

4. Discussion

The range of elbow stiffness values computed from the present study is within the range of those values previously-reported by other researchers using similar methods (Bennett et al., 1992; Lee and Ashton-Miller, 2011; Lin et al., 2005, 2003; Wiegner and Watts, 1986). The similarity of our results computed both with and without viscous damping suggests that viscous damping does not play a role in elbow stiffness at the positions and speeds investigated in this study. Thus the viscoelastic effects of the elbow joint and reflex loops do not play a role at the positions and movement speeds that are used in ADLs, as evidenced by the similarities in results for the two calculation methods, as stated above. As expected, at slow speeds, joint stiffness values tended to be greater with muscle contraction. This agrees with previous work showing that compliance decreases as perturbation movement intensity increases (Kearney and Hunter, 1982; Kearney et al., 1997; Tai et al., 1999). The rotation speed of the applied movement also increases