INTRODUCTION

The measurement of elbow joint stiffness can help diagnose, monitor, and treat patients with stiffness problems, but it is complex due to the different models [1] developed. For instance, equilibrium position control [2] and passive joint stiffness [3] use different mathematical models. Accurate measurements of joint stiffness impact the design of artificial limbs and human motor system control and simulation. The long-term research goal is to measure elbow joint stiffness in healthy and impaired subjects and quantify its change with initial elbow joint flexion angles, movement speeds, and with relaxed or contracted forearm muscles. The immediate goal was to verify that measurements made with a modified Stiffness Tester are similar to those previously reported. It was expected that elbow stiffness should increase with muscle contraction and movement speed.

METHODS

A Stiffness Tester, first developed to measure knee joint stiffness [4,5], was adapted for use with the elbow joint (Figures 1 and 2). A torque motor (Model JR24M42CH, PMI, Waltham, MA) was mounted to a steel base to drive the Stiffness Tester. An in-line torque sensor (Model 2121, LeBow Products Inc., Troy, MI) was coupled to the motor’s shaft. An aluminum forearm support, also attached to the motor’s shaft, rotated in the horizontal plane. An accelerometer (ADXL001, Analog Devices, Norwood, MA) was mounted at the end of the forearm support. Two capacitive rotary position transducers (Model 0603-0001, Transtek, Ellington, CT) provided position feedback and measured the angular displacement of the forearm.

Three healthy subjects (age 22–26, one female) volunteered for the experiment that received IRB approval from Clarkson University. Each subject’s right forearm was securely attached on the support using Velcro™ on a cloth sleeve, with the shoulder abducted 90° and the forearm fully pronated. The center of the elbow joint was aligned with the motor shaft using an axis finder modeled after Hollister et al. [6]. Ramp-and-hold motion was applied to the subject’s forearm. The forearm was extended 10° at a constant speed, held for 2 seconds, and returned to the original angular position at the same speed. Measurements were made at two initial elbow joint flexion angles, two constant speeds and two forearm muscle contraction conditions (Table 1). A grip dynamometer was used to measure the maximum grip strength of the subject before the test began. During the tests with muscle contraction, the subject held the dynamometer to maintain a grip force of 20% of his or her maximum grip strength. Each measurement was repeated three times, and there were at least 30s rest between each measurement.

Torque, acceleration, and angular displacement were measured at 500Hz using LabVIEW (NI, Austin, TX). A manually-tuned PID controller controlled the motor based on the LabVIEW-issued command. Output signals from the transducers were scaled via adjustable gain amplifiers before reaching the DAQ card (PCIe-6323, National
Instruments, Austin, TX). The data from the extension movement were analyzed.

The data were digitally filtered using a custom MATLAB (The MathWorks, Natick, MA) program with a second order low-pass Butterworth filter. The cutoff frequency for the torque and angular displacement signals was 100Hz, and 10Hz for the acceleration signal. Elbow joint stiffness, $K$, was calculated via a nonlinear least squares fit ($\text{nlinfit}$) of a mathematical model:

$$T(t) = Ja(t) + Bv(t) + K\theta(t) + C \quad (1)$$

in which $T(t) = \text{torque}$, $J = \text{moment of inertia}$, $a(t) = \text{angular acceleration}$, $B = \text{viscous damping coefficient}$, $v(t) = \text{angular velocity}$, $K = \text{stiffness coefficient}$, $\theta(t) = \text{angular displacement}$, and $C = \text{constant torque bias}$ [4]. $v(t)$ was calculated from $\theta(t)$ by numerical differentiation after filtering. $J$, $B$, $K$ and $C$ were calculated through MATLAB by application of Equation 1. The median values of each type of test are reported here.

RESULTS AND DISCUSSION

The average $C$ is $-14.19\pm0.25 \text{Nm}$ across all subjects and all tests. The small standard deviation verifies that this is a property of the machine itself. Table 1 shows the median values of each subject’s elbow joint stiffness, $K$. In general, $K$ increases with muscle contraction; increases with initial elbow joint flexion angle; and increases noticeably with the rotational speed of the forearm. Elbow joint stiffness values previously reported ranged from 2 to 40 Nm/rad [1,7]. The values measured here at the faster speed are within this range.

With muscle contraction, several two-joint muscles crossing both the elbow and wrist were activated and the elbow joint became stiffer, as seen when comparing the relaxed to contracted states in most cases, particularly with an elbow joint angle of 90°. The variability in the results shown here could be due to the difference in individuals, or they may not have been truly relaxed. When the rotational speed was lower, the elbow joint had more time to receive reflex control from the central nervous system which could have made the joint less stiff.

This marked variability in the stiffness values, particularly at the slower speed, may reflect a need to further refine the PID controller tuning, or a need to provide subjects with feedback about their muscle contraction state. In the future, we will test more subjects with different types of muscular contraction (e.g. to activate brachioradialis, triceps, or the other major movers of the elbow joint) at different joint flexion angles. Electromyography will monitor muscle forces and could be used to stimulate muscles. These studies will further verify this Stiffness Tester in its application to the elbow.

REFERENCES


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