Gender and Age Effects on Elbow Joint Stiffness in Healthy Subjects

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Objective: To investigate the effect of demographic factors on upper-limb pendulum tests in healthy subjects.

Design: Experimental. Upper-limb pendulum tests were performed on healthy subjects. Biomechanical parameters of the elbow joint were estimated. The body weight, forearm length, gender, and age of subjects were recorded. The relationships among the biomechanical parameters and demographic factors were investigated.

Setting: A referral medical center in Taiwan.

Participants: Healthy subjects (N=192).

Intervention: Upper-limb pendulum test.

Main Outcome Measures: Number of swings, relaxation indices calculated from the angle trajectories, and stiffness constants and damping coefficients estimated from the elbow model were used as the biomechanic parameters of elbow joints.

Results: Age had little effect on the biomechanic parameters. Both mean stiffness constant and damping coefficient were larger in men. However, when the influence of body weight was corrected, the biomechanic parameters were the same for both genders. Forearm length had similar but weaker effects on stiffness constant and damping coefficient.

Conclusions: In healthy subjects, the mechanical properties of the elbow joints were similar in men and women of comparable body weights and did not deteriorate significantly until subjects reached the age of 70 years.

Key Words: Age factors; Biomechanics; Body weight; Elbow; Gender; Rehabilitation.

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MUSCLE TONE IS THE PASSIVE resistance of muscle under traction and results from muscle status and connective tissue properties. In pathologic conditions, neural control is also involved... Many diseases, including spinal cord injury and stroke, and factors, such as demographic differences and nutritional state, affect muscle tone. Normal muscle tone is indicative of the grossly well-being state of the muscle and its related structures, yet few tests have objectively measured muscle tone of the upper limbs objectively. It is not a trivial matter because muscle tone of the upper and lower limbs may not be identically affected by diseases, and the respective quantification of muscle tone may be used as an objective guide for individualized treatments. Even fewer studies have investigated the muscle tone of the upper limbs in healthy subjects. A solid definition of normal muscle tone that applies widely in the general population is of fundamental importance in defining abnormal muscle tone and in quantifying the effects of physical treatments, exercises, and medications in normotonic subjects. The results also form the basis for investigating the pathophysiology of joint biomechanics.

In the previous study, we designed a simple accessory apparatus to assist subjects in performing the pendulum test in the elbow joint; we also proposed a biomechanic model of the elbow to formulate parameters for quantification. Initial results indicated that the parameters could differ between spasticity in stroke patients and normal muscle tone in healthy subjects. In that study, subjects were all older than the general population.

Our main purpose in this study was to investigate the effects of the demographic factors on the upper-limb pendulum test results in subjects with average muscle power and muscle tone. Factors such as age, gender, and body weight were chosen because it is generally perceived that men and younger persons have a better motor capability and that heavier people have greater muscle power. As far as we know, no study has specifically addressed the effects of demographic factors on muscle tone, even though such data can be useful. First, the data could facilitate the interpretation of pendulum test results in a larger population. Second, the results could be used in constructing biomechanic models of the elbow joint. The results could also help in understanding the distribution of passive joint properties in the population.

METHODS

Participants

Subjects were recruited from the outpatient clinic of National Cheng Kung University Hospital (NCKUH). Patients with a history of stroke, Parkinsonism or polyneuropathy, or neurologic deficits (eg, abnormal muscle tone, restricted range of motion, decreased muscle power) by neurologic examination were excluded. To participate, subjects had to be alert and able to follow instructions. The study protocol was approved by the NCKUH ethics committee. Before the experiment, the purpose, the potential hazard, and the procedure were explained to the subjects, who then signed the permission form. The body weight (W) and forearm length (A) were measured for the estimation of mass, center of mass, and inertia of the forearm. The test was performed on subjects’ left and right arms.

Experimental Setup and Procedure

The experimental setup and procedure are described elsewhere. In brief, we designed an accessory apparatus to facilitate performance of the pendulum test. The procedure was identical to that adopted in our previous study. After several
weight, and ma was measured by detaching the apparatus from the bed and with a balance. Ia was estimated with the method of body weight was calculated by the anthropometric formulae.\(^7\)

\[
Ia = \frac{mgL_s\sin\left(\frac{\pi}{2}\right) - m_gL_s\sin\left(\frac{\pi}{2}\right)}{2}
\]

where \(\theta\) is the elbow joint angle, \(\tau_g\) is the torque of the forearm acting on the elbow joint because of the gravitational force, \(K\) is the coefficient of stiffness of the elbow joint, \(\theta_0\) is the threshold angle for the elastic component of the connective tissue, \(C\) is the damping coefficient (also known as the coefficient of viscosity), and \(g\) is the gravitational constant. \(I_a\), \(m_a\), and \(L_a\) are the moment of inertia, mass, and length of the accessory apparatus, respectively, whereas \(I_1\), \(m_1\), and \(L_1\) are the moment of inertia, mass, and length of the forearm (including hand), respectively. Length of the forearm was defined as the distance from the ulnar head to the medial epicondyle and was measured on the skin surface along the ulnar side of the forearm. \(L_a\) and \(m_a\) are the properties of the accessory apparatus and were measured only once during the experiment set up. \(L_s\) was measured with a ruler from the center of rotation to the weight, and \(m_s\) was measured by detached the apparatus from the bed and with a balance. \(I_1\) was estimated with the method proposed by Chen.\(^6\) \(I_1\) and body weight were measured just before the experiment. \(I_1\) and \(m_1\) were calculated from \(L_1\), and body weight was calculated by the anthropometric formulae.\(^7\)

The remaining parameters of the model, that is, stiffness constant (K) and damping coefficient (C), were estimated by using the iterative optimization techniques.\(^9\) The goal of optimization was to minimize the difference between the actual and model-predicted angle trajectories.

**Data Analyses and Statistics**

First, linear regression was performed to evaluate the correlation between a parameter and the subject’s age. Second, 2-way analysis of variance (ANOVA) was used to test the significance of difference between genders. Analyses of the data showed that the men weighed more than the women. To evaluate the effect of body weight (W) on the differences of parameters between genders, K/W and C/W were calculated. Linear regression by minimization of the root mean square of errors was used to relate K and C to W, respectively. In the latter, principal component analyses were performed to investigate the relationships among parameters and their contributions to the variance. We used software StatView\(^+\) for the statistical analyses.

**RESULTS**

One hundred ninety-two qualified subjects (111 men, 81 women) completed the test. The distribution of ages and body weights for both men and women are shown in figure 2. Although there was no particular correlation between body weight and age, men weighed more than women in all age groups.

The effects of age on S and R are shown in figure 3, whereas the effects of age on model parameters K and C are shown in figure 4. The respective linear regression indicates that there was poor correlation between age and S ($r^2 = .11$), R ($r^2 = .062$), K ($r^2 = .10$), and C ($r^2 = .14$).

The effect of gender on S, R, K, and C is calculated with 2-way ANOVA. S was 4.09±1.94 for men and 5.67±2.41 for women ($F_{1,382} = 9.28, P < .05$). R for men was 1.45±0.20 and 1.31±0.18 for women ($F_{1,382} = 50.56, P < .05$). In men, K was 2.62±1.04Nm/rad and in women it was 2.26±0.87Nm/rad ($F_{1,382} = 13.34, P < .05$). C in men was .73±0.40Nm/rad\(^{-1}\), and in women, it was .53±0.40Nm/rad\(^{-1}\) ($F_{1,382} = 23.32, P < .05$). All 4 parameters differed significantly between the genders. The results indicate that gender affected the performance of the pendulum test.

The age distributions of K/W and C/W are shown in figure 5. Group mean and significance of the difference between genders were calculated. For men, K/W was .040±0.015Nm/rad\(^{-1}\)kg\(^{-1}\), for women, it was .041±0.018Nm/rad\(^{-1}\)kg\(^{-1}\) ($F_{1,382} = .830, P = .36$). For men, C/W was .011±.0064Nm/rad\(^{-1}\)kg\(^{-1}\); for women, it was .010±.0084Nm/rad\(^{-1}\)kg\(^{-1}\) ($F_{1,382} = 3.71, P = .055$). In short, there were no significant differences between men and women in K/W and C/W. The results indicate that the differences in K and C between genders were due to the differences in body weight. When all subjects were pooled
together, K and C were expressed as functions of W by linear regression as $K = 0.373W^{0.1796}$ and $C = 0.0089W^{0.1013}$, respectively.

Although the linear correlation between forearm length (A) and W was not very strong ($r^2 = 0.28$), A’s effect on K and C was similar to, but weaker than, W’s effect.

We used principal component analyses to evaluate the relationships among parameters and the respective contribution of the grouped factors (Table 1). The results showed that the parameters were grouped into 4 factors. Factor 1 (mainly S, R, and B) contributed 40.6% of the variance, factor 2 (mainly W, A, and gender) contributed 18.6%, factor 3 (mainly W and K) contributed 14.0%, and factor 4 (mainly age) contributed 9.1%. In other words, there were 4 independent groups of parameters. The first was related to viscosity, the second to body weight and gender, the third to stiffness and body weight, and the fourth to age.

DISCUSSION

Because the mechanical properties of the elbow joint are nonlinear, the values of experimentally derived constants depend on the assumptions, the test conditions, and the range of movements. It is difficult to compare the results of different studies. The estimated stiffness constants of the healthy subjects (2.62Nm/rad for men, 2.26Nm/rad for women) in our study are in general agreement with the published data (range, 0.74–4.0Nm/rad). Estimated damping coefficients (0.73Nm.s.rad$^{-1}$ for men, 0.53Nm.s.rad$^{-1}$ for women) were larger than the values reported by MacKay et al. Because the sizes of previous series were small, we expected the parameters in a larger series such as ours to have wider ranges of values. In addition, different experimental setups could have a large influence on the estimates of the damping coefficient. Because S and R are unique parameters to the pendulum test, there are no other data for comparison. Their values also depend on the design and properties of the custom-made apparatus.

Implications of the Results

It is possible that the effects of W on K and C are actually because of the mass of a muscle or the size of a joint. A larger muscle is expected to have proportionally more contractile and passive elements. The amplitudes of K and C depend on the volume of passive elements. Although it is known that a larger muscle produces a larger muscle force, no data show that, in the passive state, C is larger in a larger muscle or joint. Wiegner and Watts, in a small series, showed that K correlated linearly with arm volume. There is insufficient data about the

Table 1: Principal Component Analyses

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
<th>Factor 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forearm length (A)</td>
<td>-.144</td>
<td>.760</td>
<td>.036</td>
<td>-.139</td>
</tr>
<tr>
<td>Body weight (W)</td>
<td>-.007</td>
<td>.601</td>
<td>.454</td>
<td>-.146</td>
</tr>
<tr>
<td>Gender</td>
<td>-.011</td>
<td>-.876</td>
<td>.144</td>
<td>-.237</td>
</tr>
<tr>
<td>Age</td>
<td>-.038</td>
<td>&lt;-.001</td>
<td>.091</td>
<td>.904</td>
</tr>
<tr>
<td>No. of swings (S)</td>
<td>.785</td>
<td>-.208</td>
<td>.227</td>
<td>.026</td>
</tr>
<tr>
<td>Relaxation index (R)</td>
<td>.809</td>
<td>.018</td>
<td>-.098</td>
<td>.053</td>
</tr>
<tr>
<td>Damping coefficient (C)</td>
<td>-.778</td>
<td>-.023</td>
<td>.183</td>
<td>.145</td>
</tr>
<tr>
<td>Stiffness constant (K)</td>
<td>&lt;-.001</td>
<td>.012</td>
<td>.859</td>
<td>.152</td>
</tr>
</tbody>
</table>

NOTE. Boldface denotes larger contributions.
difference in the biomechanic properties of joints between genders. The study by Wiegner and Watts\(^2\) showed that, after correcting for the effect of arm volume, \(K\) became independent of age and gender. Our data indicate that, after correcting for the effect of body weight, there is no difference between genders in the passive properties (\(K, C\)) of the elbow joint. Because we did not measure arm length and circumference, we did not possess data on the correlation between body weights and arm volumes in our subjects.

Our results also showed that the passive biomechanic properties of the elbow joints were in the same range for all age groups, as long as the manual test indicated that it was normal. This conclusion simplifies the interpretation of pendulum test results and construction of elbow joint models. The results do not imply that the mean properties from a random sampling in the general community are identical in all age groups. Many diseases (eg, stroke, Parkinsonism) have a higher incidence in older people. These patients have different passive biomechanic properties. Our results only imply that, as long as the manual test indicates that the muscle force and muscle tone across the elbow joint are normal, the quantitative parameters of the elbow joint have similar values for all tested age groups.

**Extension From This Study**

Because the passive properties of elbow joint were independent of gender and age, and correlated approximately linearly with body weight, our results can be applied to a wide segment of the healthy population. It can be used for comparison purposes in future studies of subjects with abnormal muscle tones. We did not investigate the effects of various exercises and specific training, such as gymnastics and physical therapies, on the muscle tone of healthy subjects. These studies, which can be performed in a manner similar to our current study, will clarify the differential effects of various training protocols on muscle power and muscle tone.

Most studies on muscle tone have concentrated on hypertonia, such as spasticity and rigidity, and utilized human muscle\(^12,13\) or large robots\(^3,14\) to generate torques. Using human muscle presents a problem of inconsistency and imprecision; robots present the problem of large inertia. These methods are less likely to be useful in evaluating hypotonia, which is seen in many diseases such as cerebellar lesions, polynuropathies, and muscle diseases. In clinical practice, there is no widely accepted objective scale for evaluating hypotonia, and it is unsatisfactorily evaluated by observing hyperextensibility of the joints. It is possible that our test can be used with patients with hypotonia; we are currently working in this direction. It can also be applied to quantify the effects of drugs on muscle tone in healthy subjects, not an insignificant problem. Many patients complain about general malaise or fatigue after taking some medications. It is important to know whether the drugs cause such feelings because they affect muscle power or muscle tone.

**CONCLUSIONS**

Our study showed that, in healthy adults, the passive elbow joint properties were independent of age, after eliminating the effects of body weight and gender. The results imply that, in healthy subjects, the mechanical properties of the elbow joints are similar between men and women of comparable body weights and do not deteriorate significantly until subjects reach the age of 70 years.

**References**


**Supplier**

a. SAS Institute Inc, 100 SAS Campus Dr, Cary, NC 27513.