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Dependence of elbow viscoelastic behavior on speed and loading in voluntary movements

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Abstract. The objective of this study was to characterize the mechanical behavior of the elbow joint during voluntary movement, for different speeds of movement and under different loading conditions. Torque pulses of 50 ms duration were applied at movement onset and at peak velocity on random trials. The displacement away from the unperturbed trajectory was used as an indicator of the relative compliance of the elbow under different conditions. We found that both the displacement and the time taken to return to the unperturbed trajectory decreased if the overall speed of the movement increased or if a viscous resistive load was added, implying lower joint compliance. It was possible to account qualitatively for differences in mechanical behavior from observed muscle activation patterns.

Key words: Elbow – Compliance – Voluntary movement – Reflex – Human

Introduction

Although a considerable amount of research has been conducted to characterize the viscoelastic properties of single joints under static conditions where subjects attempt to maintain various levels of steady contraction (Joyce et al. 1974; Agarwal and Gottlieb 1977; Zahalak and Heyman 1979; Cannon and Zahalak 1982; Hunter and Kearney 1982; Gielen et al. 1984; Weiss et al. 1986; Gottlieb and Agarwal 1988; Sinkjaer et al. 1988; De Serres and Milner 1991), very little is known about how these properties are modified during voluntary movement when both muscle length and activation are changing (Bennett et al. 1992). Under static conditions, joint stiffness and viscosity vary with both muscle length (Gottlieb and Agarwal 1978; Weiss et al. 1986) and activation (Cannon and Zahalak 1982; Weiss et al. 1988). However, additional factors such as the velocity dependency of muscle force may play a significant role in determining the mechanical behavior of a joint during voluntary movement. Furthermore, since muscle activation is normally modulated by the action of feedback from sensory receptors and since both receptor sensitivity and feedback gain may change during movement (Houk et al. 1981; Soechting et al. 1981; Akazawa et al. 1982; Murphy et al. 1984; Capaday and Stein 1986, 1987), any prediction of joint viscoelastic behavior during voluntary movement based on data derived from experiments conducted under static conditions is likely to be unreliable.

As a first attempt to characterize the mechanical properties of a joint during voluntary movement, we focussed on the response of the forearm to relatively large torque pulses applied during elbow flexion and extension. We were interested in how these responses varied with the speed of the movement and how they were influenced by the level of muscle activation. To this end we compared the mechanical behavior of the elbow joint when voluntary movement involved only an inertial load and when an additional viscous load was present.

Materials and methods

Two healthy male subjects (aged 23 and 33 years) participated in this study. Neither had any history of neuromuscular injury or neurological disorder affecting the muscles or nervous system associated with movement of the elbow.

The experimental apparatus consisted of a torque motor coupled to an aluminum T-beam. The coupler was instrumented with strain gauges in order to measure the torque applied by the subject to the motor shaft. The apparatus was also instrumented with a potentiometer and a tachometer coupled to the motor shaft by means of antibacklash gears and an accelerometer attached to the T-beam.

Subjects were seated comfortably in a chair with the forearm supported by the beam, at a height which kept the upper arm in a horizontal position. The forearm was tightly secured within a thermoplastic brace that was custom-fitted to the individual subject. The brace was rigidly bolted to the T-beam.

Surface electromyographic activity (EMG) was recorded with four active bipolar electrodes (Liberty Mutual) which had a passband of 45–550 Hz. Electrodes were placed on the brachioradialis, biceps, and lateral and long heads of triceps. EMG, torque, position, velocity, and acceleration signals were amplified and digitized at a sampling frequency of 1500 Hz.

Two light-emitting diode (LED) targets were positioned 0.70 radians (rad) apart with the midway point corresponding to an angle of 1.57 rad (90°) between the upper arm and forearm. Subjects alternately made flexion and extension movements from one target to the other, coming to a complete stop at each target. After each movement, peak velocity was displayed together with a velocity target (4 rad/s, 3 rad/s, or 2 rad/s).

In the first experiment, the external load consisted only of the inertia of the apparatus. Subjects performed blocks of 220 movements (110 in each direction) for each target velocity. In a second experiment, negative velocity feedback to the torque motor was used to produce a viscosity of $1.03\ \mathrm{Nm/rad \cdot s^{-1}}$. Subjects performed blocks of 400 movements (200 in each direction) for each target velocity in this experiment.

The first 20 and last 20 trials of each block were unperturbed. On the remainder of the trials, perturbations were applied on random trials such that one-third of the trials were perturbed. In the first experiment there were four possible perturbations: (1) torque pulse assisting movement at movement onset; (2) torque pulse opposing movement at movement onset; (3) torque pulse assisting movement at peak velocity; and (4) torque pulse opposing movement at peak velocity. In the second experiment, two additional perturbations were applied, which are described below. The type of perturbation was chosen randomly for each perturbed trial. Each perturbation was applied a total of ten times for each movement direction. The torque pulses were 5 Nm in amplitude and 50 ms in duration. The first 20, the last 20, and the perturbed trials were stored for later analysis.

In the first experiment (inertial load), the ensemble mean of the unperturbed trajectories was subtracted from the mean trajectory obtained under each perturbation condition, leaving only the response to the perturbation.

In the second experiment (viscous loading), we applied either pure unloading perturbations or pulse perturbations, followed immediately by unloading. The unloading consisted of abruptly reducing the motor torque to zero. As in the first experiment, these perturbations were timed either to coincide with movement onset or peak velocity (Fig. 1). For each of the four conditions listed above, the mean trajectory obtained with the pure unloading perturbation was subtracted from the mean trajectory with the pulse perturbation, followed by unloading. Note that the pulse perturbation simply consisted of holding the torque at 5 Nm for 50 ms.

Results

The principal objective of this study was to determine how the speed of a voluntary movement affected the mechanical response of the forearm and elbow to perturbations applied at the onset and midpoint of the movement. In order to isolate the effect of the perturbation it was first necessary to demonstrate that until the time of the perturbation, the kinematics of perturbed movements did not differ from the kinematics of the unperturbed movements. The ensemble means of unperturbed and perturbed movement trajectories are shown in Fig. 1. They are nearly identical up to the point at which the perturbation was applied. Hence, we can have confidence that the motor commands were essentially the same in unperturbed and perturbed trials.

EMG responses

The EMG for flexion and extension movements was generally characterized by a two-burst (agonist/antagonist) pattern. As movement speed increased, the amplitude of the bursts increased, their duration decreased, and antagonist muscles were activated sooner following movement onset. When the viscous load was added, the amount of agonist muscle activity increased both in amplitude and duration compared with the inertial load alone, while the antagonist muscle activity decreased (Fig. 1).

Reflex modulation of muscle activity in response to the perturbation could be ascertained by comparing the EMG recorded during perturbed movements with that recorded during unperturbed movements. Phasic changes in muscle activity began with a relatively short latency following the onset of the perturbation (approximately 25 ms), although the total duration was often more than 100 ms. We did not attempt to separate the responses into short and long latency components.

The effect of the perturbation on the activity of a muscle was consistent with what would be expected if that muscle was either briefly stretched or shortened by the perturbation. A perturbation opposing movement was excitatory to agonist muscles and inhibitory to antagonist muscles, while the reverse was the case when the perturbation assisted movement. Excitatory (inhibitory) effects were manifested as an advance (delay) in onset of muscle activation, an increase (decrease) in amplitude and/or an increase (decrease) in duration, depending on the level of activity already existing. For example, in Fig. 1 agonist activity is prolonged and antagonist activity delayed when a perturbation is applied at movement onset, while the same perturbation applied at peak velocity excites the silent agonists but has a minimal effect on the antagonists (the late excitation which is seen is probably a voluntary response).

Mechanical responses

As overall movement speed decreased from a target peak velocity of 4 rad/s to 2 rad/s, both the amplitude and duration of the displacement produced by the torque pulse increased (Fig. 2A), indicating an increase in elbow compliance. The response far outlasted the 50-ms torque pulse, returning to the unperturbed trajectory only after about 250 ms in the case of the fastest movements and considerably later (>400 ms) for the slowest movements. This inverse relation between movement speed and elbow compliance was a consistent finding for any combination of conditions (movement direction, perturbation direction, and movement phase, i.e., onset or peak velocity).

The effect persisted when a viscous load was added, although the relative amplitude and duration of the response were reduced at any given movement speed, indicating a general decrease in elbow compliance. The latter effect is illustrated in Fig. 2B. Again, this was a consistent finding for any combination of conditions, but the

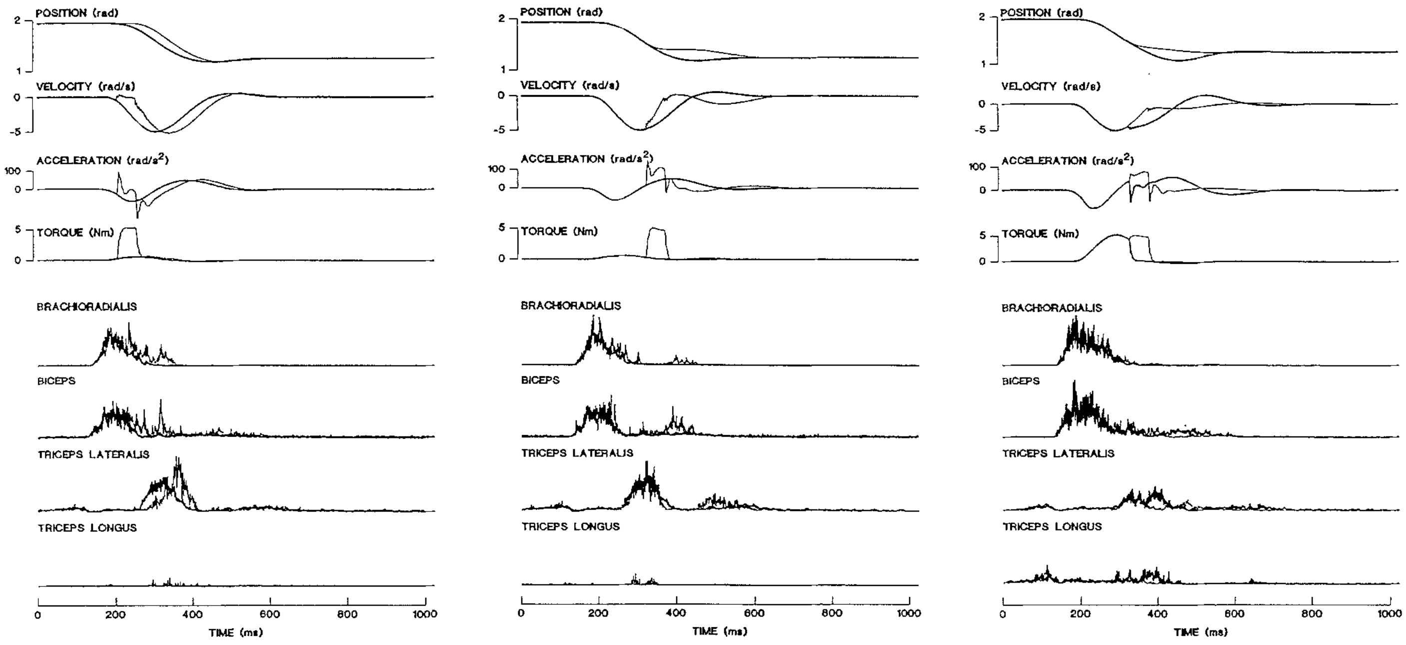

Fig. 1. Ensemble means of unperturbed and perturbed flexion movements, target velocity 4 radians per second (rad/s). *Left,* inertial load only; pulse opposing movement applied at movement onset. *Center,* inertial load only; pulse opposing movement applied at peak velocity. *Right,* added viscous load; unloading (*thick lines*) and pulse opposing movement followed by unloading (*thin lines*)

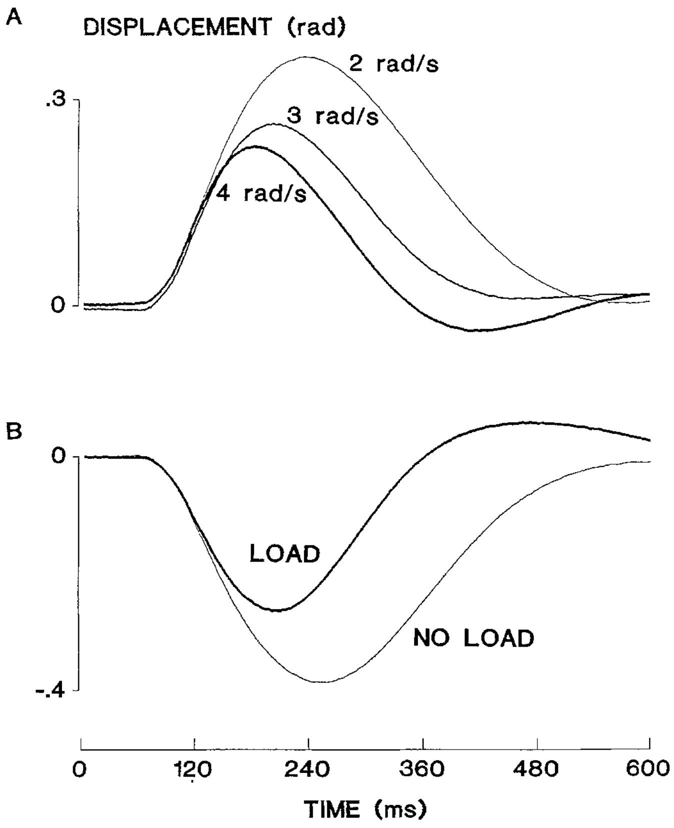

Fig. 2 A, B. Displacement produced by torque pulse (mean perturbed trajectory minus mean unperturbed trajectory). **A** Comparison of displacement for different target velocities. **B** Comparison of displacement with and without a viscous resistive load, target velocity 2 radians per second (rad/s)

size of the effect diminished as movement speed increased.

The amplitude of the displacement produced by a torque pulse when the arm was relaxed was substantially greater than that produced when the pulse was applied at approximately the same position just after the arm had begun to move. In the former case the displacement was 0.7–0.75 rad while in the latter it varied from about 0.4 rad when the target velocity was 2 rad/s to less than 0.25 rad when it was 4 rad/s.

Discussion

The finding that both the displacement and the time to return to the unperturbed trajectory decreased if the overall speed of the movement increased or if a viscous resistive load was added can be explained by the fact that greater voluntary muscle activation was necessary to move faster or to move against the load. In both cases this would have resulted in a greater number of attached cross-bridges resisting the torque pulse and hence reducing the amplitude of the resulting displacement. The active stiffness of isolated muscle has usually been modeled as the sum of the stiffnesses of all attached cross-bridges, presumed to act as parallel elastic elements. Increased muscle stiffness due to more attached cross-bridges would also explain the more rapid return to the unperturbed trajectory.

Reflex responses due to muscle stretch or shortening produced by the perturbation also contributed to the return of the elbow to the unperturbed trajectory. However, the magnitude of these responses was similar during slow and fast movements and therefore could not account for the inverse relation between movement speed and compliance.

Bennett et al. (1992) reported that stiffness was lower during movement than during maintained posture, whereas we found that even during relatively slow movement the displacement produced by the torque pulse was much less than during relaxed posture. The most probable explanation for this difference is that the subjects in the experiments of Bennett et al. were not completely relaxed (Bennett, personal communication), since they were asked to maintain posture while being subjected to random perturbations.

The results of our study suggest that differences in displacement produced by a torque pulse (elbow compliance) observed under a number of different conditions during voluntary movement can be largely accounted for by differences in muscle activation present at the time that the torque pulse is applied. This is not to imply that EMG provides a direct measure of the joint compliance, since changes in muscle force are delayed with respect to changes in EMG and are also more gradual. In particular, it must be kept in mind that a muscle continues to generate force for some time after it becomes electromyographically silent, owing to a relatively long mechanical time constant compared with its electrical time constant. Nevertheless, we can conclude than changes in muscle activation are in large part responsible for changes in viscoelastic behavior during voluntary movement.

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