A mechanical study of the moment-forces of the supinators and pronators of the forearm

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ABSTRACT – We determined the torque generated by the muscles rotating the forearm at varying degrees of pronation and supination. We used 8 human cadaveric upper extremity specimens with the humerus and ulna rigidly fixed with the elbow in 90° of flexion, while free rotation of the radius around the ulna was allowed. The tendons of the flexor carpi ulnaris (FCU), extensor carpi ulnaris (ECU), supinator, biceps, pronator teres (PT), and the pronator quadratus' (PQ) superficial and deep heads were isolated. After locking the forearm at intervals of 10° from 90° of pronation to 90° of supination, we loaded each muscle/tendon with a ramp profile.

We found that the biceps and supinator are both active supinators, the biceps generating four times more torque with the forearm in a pronated position. As for pronation, the PT and both heads of the PQ are active throughout the whole rotation, being most efficient around the neutral position of the forearm. The ECU and FCU contribute significantly less to pronation and supination torque. However, they do generate potential pronating torque while the forearm is positioned maximally in supination and, to a lesser extent, potential supination torque while the forearm is positioned maximally in pronation.

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Forearm rotation occurs through the articulations of the radius and ulna at the proximal and distal radioulnar joints. By convention, the pronating muscles have been defined as the pronator teres and the pronator quadratus, and the supinators have been identified as the biceps brachii and the supinator. However, we have no information about how much torque is generated by these muscles and if these values change with varying degrees of forearm rotation. Moreover, the torque generating potential of additional musculotendinous units which cross between the radius and ulna or cross the wrist is unknown. This information is essential for a full understanding of the normal muscular action of the forearm and would help in predicting the advantages and disadvantages of various tendon transfers involving these muscles.

During the development of a dynamic simulator designed especially to evaluate the mechanics of the distal radioulnar joint, it became clear that the torque profiles of the major musculotendinous units crossing the forearm and wrist must be defined to simulate the physiologic loading of these muscles (Haugstvedt et al. 2001). This study was done to determine the torque generated by the muscles rotating the forearm at varying degrees of pronation and supination.

Material and methods

8 fresh-frozen cadaveric upper extremity specimens (5 males), with a median age of 65 (41–90) years, were used. These included the entire upper extremity distal to a mid-humerus amputation level. Each specimen was obtained through the Department of Anatomy Deeded Body Program and all provisions concerning ethics were observed. Medical histories of the donors were reviewed and radiographs of the specimens before testing were used to rule out any conditions which might adversely affect the results. After thawing at room temperature overnight (Viidik et al. 1965), the specimens

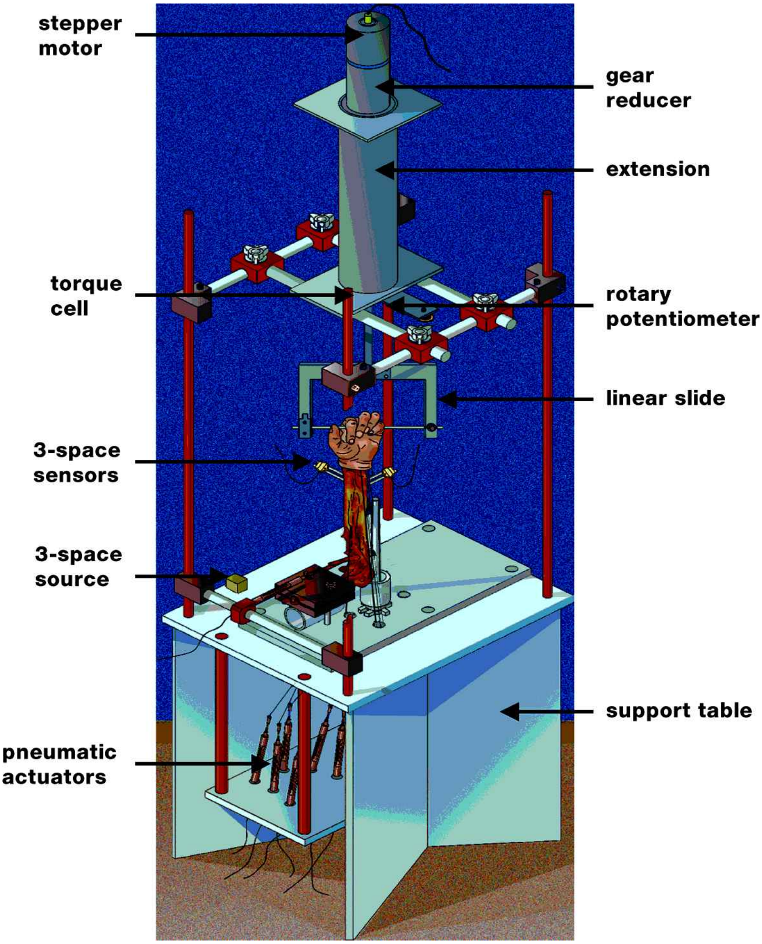


Figure 1. A schematic drawing of a forearm simulator showing the humerus of the specimen fixed to the examining table while the forearm is rotated around the fixed ulna. While the forearm was locked at intervals of 10º, the torque cell recorded the axial torque across the wrist and the potentiometer defined the position of the specimen (see text for further details).

were mounted on the testing machine and passively manipulated to verify that at least 80° of pronation and supination was possible. Preparation before testing involved removal of all the skin, muscles and tendons, except the muscles to be loaded. The capsule and ligamentous structures around the elbow and wrist were left intact.

The elbow was fixed at 90° of flexion with the humerus and ulna solidly fixed to the testing machine while the radius was allowed to rotate freely around the ulna (Figure 1) (Haugstvedt et al. 2001). The muscles to be loaded were the FCU, ECU, PT, the superficial and deep heads of the PQ (Johnson and Shrewsbury 1976, Stuart 1996), the supinator, and biceps. The muscle tendons were attached through sutures to cables routed through grommets and pulleys to pneumatic low-friction cylinders. The orientation of the cables was routed to simulate the appropriate line of action for each muscle. The wrist/hand segment was left unconstrained relative to the forearm. The specimen was passed through 10 cycles of pronation and supination for preconditioning. A torque cell was mounted to record the axial torque across the wrist, and a potentiometer defined the position (rotation) of the specimen in the metacarpal region relative to the ulna. After we locked the forearm by fixing the metacarpal position at intervals of 10° from the maximum pronated position to the maximum supinated position, each muscle/tendon unit being tested was loaded with a ramp profile through a pneumatic actuator driven by a servo pneumatic valve under PC control. For each muscle the torque and muscle loading were recorded in each of the various positions.

Results

The torque/muscle load relationship was linear for each angle for all of the muscles tested, as shown for the biceps in Figure 2. By calculating the slope of the torque per muscle force (Ncm/N) for each of the muscles tested, Δt/Δf, the moment arm was graphed as a function of angle. The results of plotting the torque per muscle force (Ncm/N) for each of the muscles tested are shown in Figures 3a–g. In each figure, the plotted points represent the mean

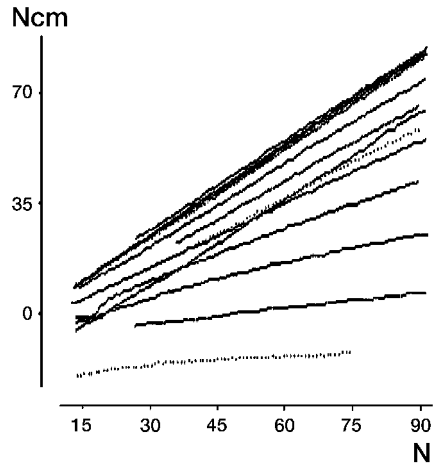
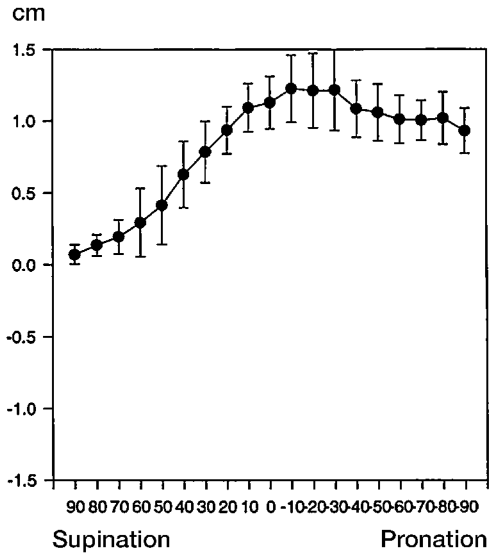
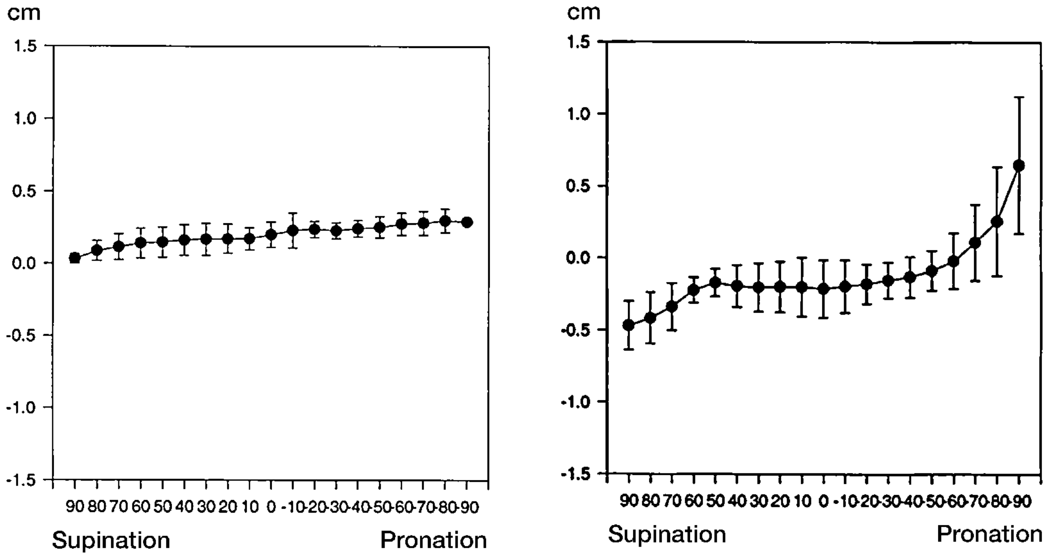


Figure 2. Each line indicates the relationship between the torque generated and the muscle load applied at a certain angle. This relationship was linear for each angle and for all the muscles tested. In this figure, the biceps is used as an example.



a. The biceps



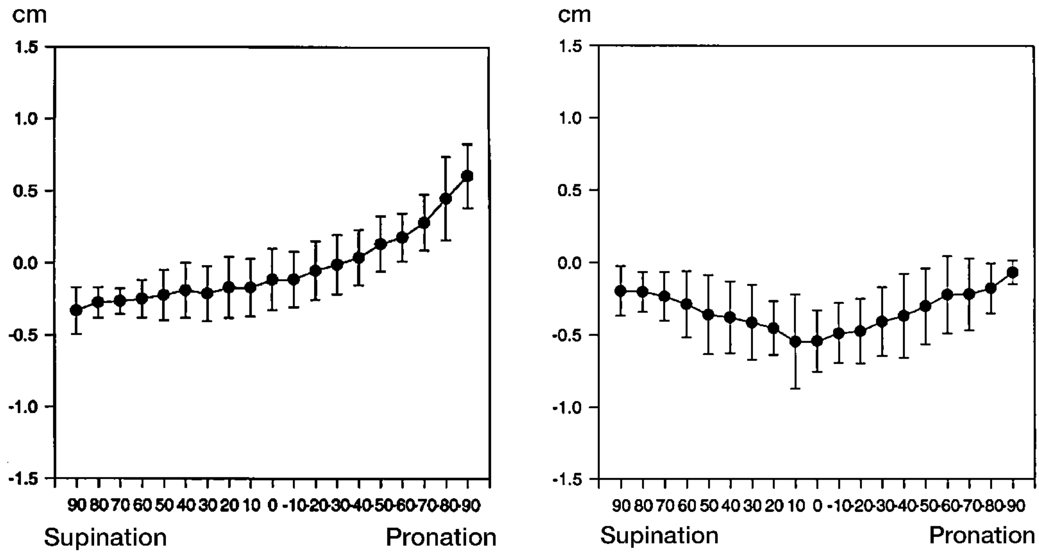
b. The supinator

c. The extensor carpi ulnaris

Figure 3. When we calculated the slope of the torque per muscle force (Ncm/N) for each of the muscles tested, the moment arm could be graphed as a function of angle. The plotted points correspond to the mean values for all specimens tested and the vertical bars for each point define the standard deviation. A negative torque value simply represents a momentforce in the opposite direction as a positive value.

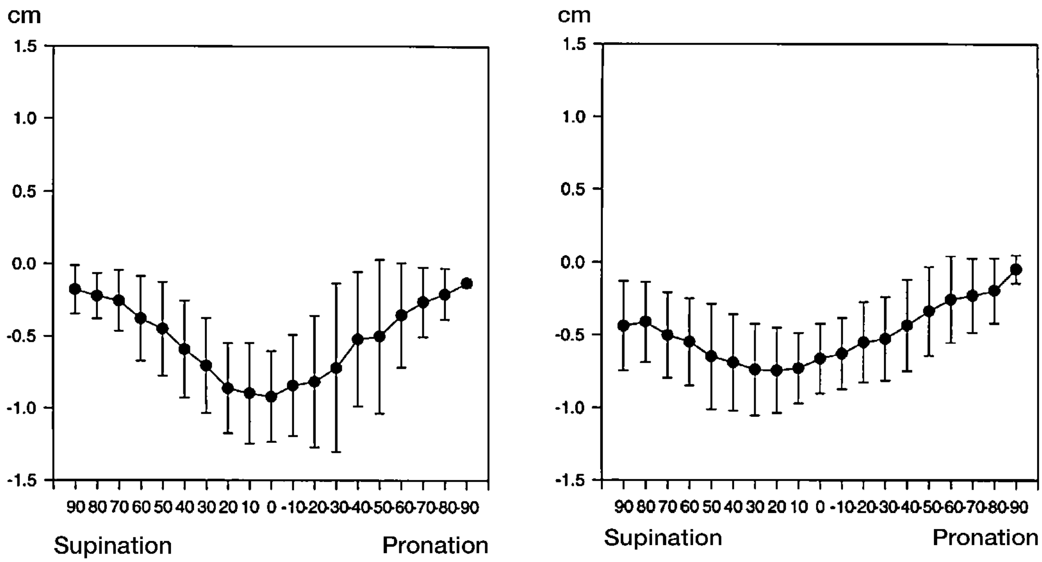
values of all specimens tested and the vertical bars for each point define the standard deviation. A negative torque value simply represents a momentforce in the opposite direction as a positive value.

The biceps brachii and supinator are both active supinators. The biceps brachii can generate four times more torque than the supinator with the forearm in a pronated position (Figures 3a and b). The pronator teres and both the heads of the pronator quadratus generate torque throughout the entire range of rotation, being most efficient around the neutral position of the forearm (Figures 3e, 3f and



d. The flexor carpi ulnaris

e. The deep head of the pronator quadratus



f. The superficial head of the pronator quadratus

g. The pronator teres

3g). The extensor and flexor carpi ulnaris contribute significantly less to pronation and supination torque than the muscles mentioned above (Figures 3c and 3d). However, they generate potential pronating torque while the forearm is positioned maximally in supination and to a lesser extent generating potential supination torque while the forearm is positioned maximally in pronation.

Discussion

Our observations increase understanding of how much each muscle may contribute ratiometrically to the rotational torque across the wrist in different positions throughout supination and pronation of the forearm. One should note, however, that observations are made from in vitro studies of individual muscles. This, of course, may not necessarily reflect how these same muscles behave in vivo, where several muscles are active at a given time, in both agonist and antagonist roles. This information has subsequently been used as a foundation for defining the loading parameters for a dynamic distal radioulnar joint simulator (Haugstvedt et al. 2001). Other research groups use different methods or feed-back systems for loading muscles on a dynamic joint simulator (Werner et al. 1996, Dunning et al. 1998).

It has been established that slow unresisted supination is brought about by the independent action of the supinator, while fast resisted and unresisted supination are assisted by the action of the biceps (Basmajian and Deluca 1985). We found minimal torque generated from the supinator and biceps brachii muscles while the forearm is in a supinated position. As the forearm moves into a pronated position, the torque generated increases, reaching its maximum for the biceps brachii at approximately 20° of pronation. In this position, the torque generated by the biceps brachii tendon is about four times greater than the torque generated by the supinator muscle, the latter generating a torque that is relatively consistent throughout rotation of the forearm. Our results support the findings of the primacy of the supinator during unresisted movement, while supination against resistance requires the cooperation of the biceps brachii in varying degrees (Basmajian and Deluca 1985).

While the forearm is in the maximally supinated position, there is no torque generated from the pronator teres or pronator quadratus muscles. However, in this position, the torque potential of the extensor and flexor carpi ulnaris muscles would be sufficient to pronate the forearm. From our study, it seems likely that the flexor and extensor carpi ulnaris muscles may be responsible for initiating pronation from the maximally supinated position. This concept makes more plausible the previous explanation that the natural elastic recoil of the pronator muscles from complete supination would be enough to initiate pronation (de Sousa et al. 1957, 1958). The torque generated from the pronator quadratus and pronator teres reached a maximum as neutral forearm rotation is approached, decreasing as the forearm moves toward a supinated position. There were small differences in the torque generated from the three muscle heads. However, the data have shown that the deep and superficial heads of the pronator quadratus generate more torque together than the isolated pronator teres. This correlates well with electrophysiologic studies which show that while both the pronator quadratus and the pronator teres are active during pronation, the consistent prime pronating muscle is the pronator quadratus (Basmajian and Deluca 1985).

One of the standard surgical treatments for radial nerve palsy is to transfer the pronator teres to the radial wrist extensors (Green 1988). Our findings suggest that the two heads of the pronator quadratus may create sufficient torque for pronation after the loss of the pronator teres for the tendon transfer. The total simultaneous torque of all three pronator muscle heads was not tested in this experiment.

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