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Technical note

Simulation of elbow and forearm motion in vitro using a load controlled testing apparatus

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Abstract

The purpose of this study was to compare passive to active testing on the kinematics of the elbow and forearm using a load-controlled testing apparatus that simulates muscle loading. Ten fresh-frozen upper extremities were tested. Active control was achieved by employing computer-controlled pneumatic actuators attached to the tendons of the brachialis, biceps, triceps, brachioradialis and pronator teres. Motion of the radius and ulna relative to the humerus was measured with an electromagnetic tracking system. Active elbow flexion produced more repeatable motion of the radius and ulna than when tested passively ($p < 0.05$). The decrease in variability, as determined from the standard deviation of five successive trials in each specimen, was 76.5 and 58.0% for the varus–valgus and internal–external motions respectively (of the ulna relative to the humerus). The variability in flexion during simulated active forearm supination was 30.6% less than during passive testing. Thus under passive control, in the absence of stability provided by muscular loading across the joint, these uncontrolled motions produce increased variability amongst trials. The smooth and repeatable motions resulting from active control, that probably model more closely the physiologic state, appear to be beneficial in the evaluation of unconstrained kinematics of the intact elbow and forearm. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Elbow; Kinematics; Motion simulation; Forearm; Repeatability

1. Introduction

Biomechanical in vitro testing of the elbow and forearm, particularly the investigation of joint kinematics, has been the subject of numerous studies. Olsen et al. (1994) described a system to determine the kinematics of elbow during passive flexion–extension with varying degrees of applied varus–valgus and internal–external moments. Other studies employing this apparatus have focused on elbow ligament insufficiencies (Olsen et al., 1996; Sojbjerg et al., 1987a,b). Morrey et al. (1991) described a testing apparatus to quantify the passive kinematics of the elbow. Weights were applied to simulate dynamic (muscle) stabilizers while the elbow was manually flexed. A similar device has been used to assess a number of variables related to the elbow, including ligament injuries and elbow replacements (Itoi et al., 1994; King et al., 1993a,b,1994; O'Driscoll et al., 1992).

Apart from these studies, we are unaware of a comprehensive upper limb loading apparatus that uses active tendon control to permit in vitro testing of elbow and forearm disorders. A testing device that produces motion actively by prescribed tendon loading, may be beneficial from the viewpoint of modelling unconstrained and physiologic motions.

The aim of this study was to evaluate a testing apparatus that simulates active muscle loading to achieve elbow and forearm motion. The dependent variable measured was the motion of both the radius and ulna. We established a loading scheme to simulate elbow flexion and forearm rotation, and compared the repeatability of the output motion of passive to active testing.

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2. Methods and materials

The principal function of the testing apparatus was to provide independent load control to the tendons, and hence motion, of the cadaveric forearm (Fig. 1). The (humeral) mounting clamp provided rigid fixation of the specimen, while assuring sufficient clearance for the tendons and cables. The tendon alignment system was designed to ensure that the line of action of tendon loading could be adjusted to any position in the transverse plane, to replicate muscle position (An et al., 1981,1984; Murray et al., 1995). Additionally, in order to maintain the muscle moment arms at the elbow as physiologic as permitted, the soft tissue and skin were kept intact up to the distal one-fourth of the humerus. This system was employed for modelling of the biceps, triceps, and brachialis muscles.

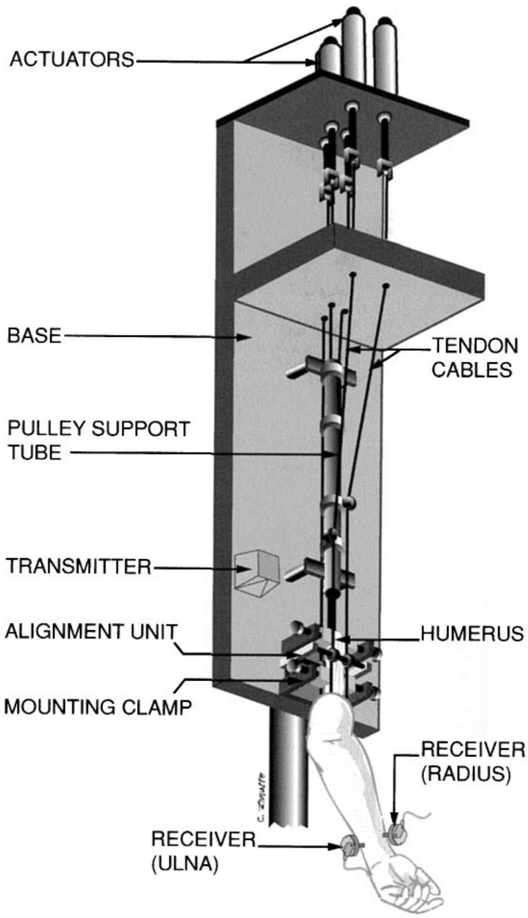

Fig. 1. The testing apparatus used to apply independent loads to tendons while measuring relative motion of the ulna and radius (relative to the humerus). The specimen is fixed in the mounting clamp and loads are applied by (pneumatic) actuators to cables sutured to tendons. The electromagnetic tracking system transmitter is attached to the base, and the receivers are secured to the ulna and radius. Alignment of the tendon cables for the biceps, brachialis and triceps is achieved with an alignment unit and the pulleys attached to the support tube. Tendon cables for the pronator teres and brachioradialis pass through the pulley support tube.

The lines of action of the brachioradialis and pronator teres were simulated by passing the cables through delrin sleeves implanted at their origins in the distal humerus. The cables were passed through the intramedullary canal, the pulley support tube, and to the respective actuators.

Muscle loads were simulated using computer-controlled pneumatic actuators (SR-066-DXP, Bore size = 2.22 cm, BIMBA Ltd., Cambridgeshire, UK). Stainless steel cables (0.8 mm diameter) were sutured into the distal tendon of each muscle and secured to the actuators. Proportional pressure controllers (PPC, MAC Valves, Wixon, MI, USA) controlled by a custom-written program (LabVIEW, National Instruments, Texas, USA) enabled the sequential timing and loading of each actuator to be individually controlled. An iterative loading protocol was conducted on each specimen to determine the minimum load necessary to produce quasi-static flexion motion of the elbow with the humerus orientated vertically. The magnitudes of brachialis, biceps, brachioradialis, and triceps tendon loads were derived by apportioning muscle loading in accordance with published measurements of quantitative electromyographic (EMG) activity (Funk et al., 1987) and physiological muscle cross-sectional area (CSA) (Amis et al., 1979). The ratio of muscle loading was determined from the product of the relative EMG activity and CSA data. Relative loading was thus apportioned amongst the actuators based on these ratios.

For elbow flexion (from the vertical position), the biceps was initially activated to place the forearm into the fully supinated position (Fig. 2). Since biceps activation causes elbow flexion, the triceps was also activated initially to ensure that motion started from the the fully supinated and extended position. The other two elbow flexors (brachialis and brachioradialis) were activated to produce elbow flexion. For forearm supination, loading was accomplished by applying the minimal loads to the biceps to achieve supination (Fig. 2). The early initiation of the pronator teres was to ensure supination began in the fully pronated position. The triceps activation assured that the arm was in the fully extended position prior to forearm rotation.

Motion of both the ulna and radius relative to the humerus was measured using an electromagnetic tracking system (Flock of Birds, Ascension Technology, Burlington, VT) consisting of two receivers (attached to the ulna and radius) and a transmitter (Fig. 1). Previous research conducted in our laboratory demonstrated a rotational accuracy of 1.8%, and a resolution of 0.1° (Milne et al., 1996). In order to construct clinically relevant coordinate systems, a delrin stylus secured to a third tracking system receiver was used to digitize bone landmarks of the humerus, radius, and ulna. The humeral coordinate system was derived by sphere-fitting of the capitellum, and circle-fitting of the trochlear groove and