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Short communication

Control of a wrist joint motion simulator: A phantom study

Darshan S. Shah, Angela E. Kedgley*

Department of Bioengineering, Imperial College London, London, United Kingdom

A R T I C L E I N F O

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A B S T R A C T

The presence of muscle redundancy and co-activation of agonist–antagonist pairs in vivo makes the optimization of the load distribution between muscles in physiologic joint simulators vital. This optimization is usually achieved by employing different control strategies based on position and/or force feedback. A muscle activated physiologic wrist simulator was developed to test and iteratively refine such control strategies on a functional replica of a human arm. Motions of the wrist were recreated by applying tensile loads using electromechanical actuators. Load cells were used to monitor the force applied by each muscle and an optical motion capture system was used to track joint angles of the wrist in real-time. Four control strategies were evaluated based on their kinematic error, repeatability and ability to vary co-contraction. With kinematic errors of less than 1.5°, the ability to vary co-contraction, and without the need for predefined antagonistic forces or muscle force ratios, novel control strategies – hybrid control and cascade control – were preferred over standard control strategies – position control and force control. Muscle forces obtained from hybrid and cascade control corresponded well with in vivo EMG data and muscle force data from other wrist simulators in the literature. The decoupling of the wrist axes combined with the robustness of the control strategies resulted in complex motions, like dart thrower's motion and circumduction, being accurate and repeatable. Thus, two novel strategies with repeatable kinematics and physiologically relevant muscle forces are introduced for the control of joint simulators.

1. Introduction

Muscle activated physiologic simulators recreate the kinematic and kinetic conditions of a natural joint in cadaveric specimens by applying loads to the tendons. As in other joints of the body, redundant muscle activation occurs at the wrist because six primary muscles control its two degrees of rotation. Resolution of the load distribution between the muscles is vital to solve this indeterminate problem.

A common strategy for recreating joint motion has been to control one muscle, the 'prime mover', using prescribed excursion, while other muscles, classified as either synergists or antagonists, are simulated using prescribed forces. These forces are calculated as a proportion of the prime mover force, using some combination of physiological cross-sectional area (PCSA), lever arms, electromyographic (EMG) signals, and clinical knowledge of the muscles. This strategy has been used in shoulder (Kedgley et al., 2007), elbow (Johnson et al., 2000), forearm (Nishiwaki et al., 2014) and ankle (Sharkey and Hamel, 1998) simulators.

The most widely published wrist simulator employs a control strategy based primarily on position feedback; the agonists are controlled using a signal proportional to the error in joint position, whereas antagonists maintain a constant force (Werner et al., 1996). An alternative strategy has been to employ force control, where each muscle is controlled by a predefined set of force profiles corresponding to a specified motion (Erhart et al., 2012).

The aforementioned joint simulators employ assigned force profiles, or established muscle force ratios based on EMG and/or PCSA or muscle moment arms. Hence, they have predefined (Erhart et al., 2012) or unique (Werner et al., 1996) muscle force profiles for a given joint motion. However, redundant muscle actuation allows for the possibility of multiple force distributions resulting in the same kinematics, and for the occurrence of co-contraction – the ability of groups of muscles to produce higher forces simultaneously, in order to stabilize the joint. A computational study which combined both

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* Correspondence to: Department of Bioengineering, Imperial College London, South Kensington Campus, London SW7 2AZ, United Kingdom.
E-mail addresses: darshan.shah12@imperial.ac.uk (D.S. Shah), akedgley@imperial.ac.uk (A.E. Kedgley).

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position and force control by an optimization technique to map joint torques to muscle forces suggests an additional method of joint simulator control, known as cascade control (Colbaugh and Glass, 1993). However, it has never been tried on a physiologic simulator.

The aims of this study were, therefore, to develop a repeatable muscle activated physiologic wrist simulator and to compare pre-established and novel control strategies. The hypothesis was that combining position and force feedback into one control algorithm would result in a more physiologic outcome.

2. Materials and methods

2.1. Design

Motion at the wrist was recreated by applying tensile loads using linear actuators (SMS Machine Automation, UK) mounted in-line with servo motors (Animatics Corp., CA, USA) via steel cables guided through the custom pulleys (Fig. 1). Muscles with the greatest effect on the wrist (Brand and Hollister, 1999) were considered for this study – flexor carpi radialis (FCR), flexor carpi ulnaris (FCU), extensor carpi radialis longus (ECRL), extensor carpi radialis brevis (ECRB), extensor carpi ulnaris (ECU) and abductor pollicis longus (APL). Load cells (Applied Measurements Ltd., UK) were connected in series with the actuators to monitor force applied to each tendon. A six-camera optical motion capture system (Qualisys, Sweden) was used to obtain the joint angles in real time by placing clusters of reflective markers on the hand and forearm and following ISB recommendations for joint angle calculations (Wu et al., 2005). The wrist was driven using custom-written LabVIEW code (National Instruments, TX, USA) that implemented the algorithms discussed below. These algorithms were compared in a controlled manner on a phantom limb – an artificial, functional replica of a human hand and forearm (Fig. 1a).

The phantom hand replicated a 50th-percentile male hand with an open fist. The mass and center of gravity of the hand were calculated from anthropometric data (Tilley, 2002; Winter, 2009). Tendon insertions for each wrist tendon were obtained by digitizing their locations on a 3D model of the hand created by segmenting a CT scan of a model of the upper limb (Sawbones, WA, USA) using MIMICS 16.0 (Materialise, Belgium). Co-ordinates of all tendon insertions were calculated with respect to the head of the capitate, which was assumed to be the origin (Youm et al., 1978). A pulley plate, consisting of custom-made rotating pulleys on either side, served as the flexor and extensor retinacula. The pulleys were positioned to mimic the locations of the wrist tendons with respect to the flexion-extension (FE) and radioulnar deviation (RUD) axes in the transverse plane (Brand and Hollister, 1999). Decoupling the FE and RUD axes in the wrist facilitated the replication of complex functional motions, like dart thrower's motion (DTM) or circumduction.

2.2. Control strategies

Four different control algorithms were tested. Position and force control were established strategies used on previous wrist simulators, whereas hybrid and cascade control were novel strategies.

2.2.1. Position control

Errors between the desired trajectory and actual joint angles in FE and RUD were minimized using a proportional-integral-differential (PID) controller (Fig. 2a). Optimum PID parameters were obtained by carrying out Ziegler–Nichols tests (Ziegler and Nichols, 1995) and then manually adjusting them for low steady state error, high response time and low overshoot for a step input. From the kinematic error, the excursion of the ECRB was modified, while the excursions of the remaining tendons were driven by ratios of the moment arms (additional details in Appendix A.1). Muscle moment arms were determined by performing tendon excursion tests (An et al., 1983; Bremer et al., 2006; Kuxhaus et al., 2009) and were given as input for precise distribution of relative tendon excursion.

2.2.2. Force control

Each actuator was given a custom force trajectory as the input, which reflected the force profile of the corresponding muscle for a specified motion, as determined from trials in position control. Error between the input force trajectory and actual cable forces from the load cells was minimized using a proportional-integral (PI)

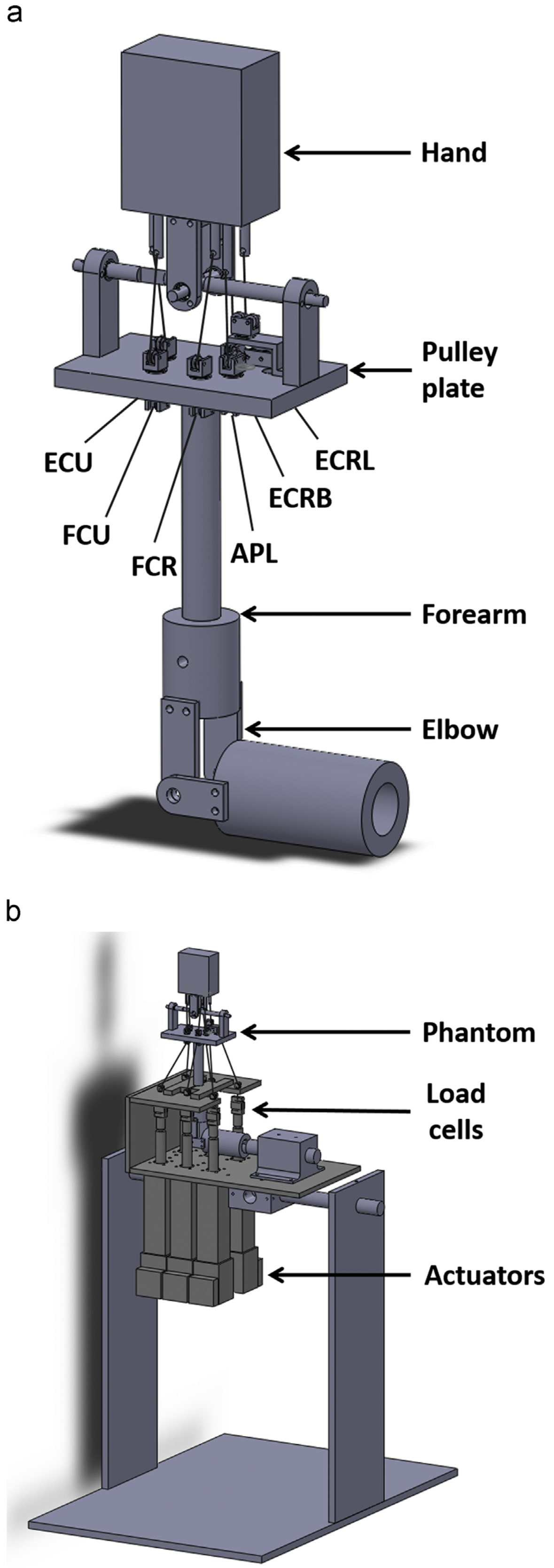

Fig. 1. A schematic diagram of (a) the phantom and (b) the wrist simulator shown in the vertically upward position (FCR = flexor carpi radialis, FCU = flexor carpi ulnaris, ECRL = extensor carpi radialis longus, ECRB = extensor carpi radialis brevis, ECU = extensor carpi ulnaris, APL = abductor pollicis longus).