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Journal of Biomechanics 38 (2005) 673–684

JOURNAL OF BIOMECHANICS

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Young Scientist Post-doctoral Award

An integrative approach to the biomechanical function and neuromuscular control of the fingers

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Accepted 4 April 2004

Abstract

The exquisite mechanical functionality and versatility of the human hand emerges from complex neuro–musculo–skeletal interactions that are not completely understood. I have found it useful to work within a theoretical/experimental paradigm that outlines the fundamental neuro–musculo–skeletal components and their interactions. In this integrative paradigm, the laws of mechanics, the specifications of the manipulation task, and the sensorimotor signals define the interactions among hand anatomy, the nervous system, and manipulation function. Thus, our collaborative research activities emphasize a firm grounding in the mechanics of finger function, insistence on anatomical detail, and meticulous characterization of muscle activity. This overview of our work on precision pinch (i.e., the ability to produce and control fingertip forces) presents some of our findings around three Research Themes: Mechanics-based quantification of manipulation ability; Anatomically realistic musculoskeletal finger models; and Neural control of finger muscles. I conclude that (i) driving the fingers to some limit of sensorimotor performance is instrumental to elucidating motor control strategies; (ii) that the cross-over of tendons from flexors to extensors in the extensor mechanism is needed to produce force in every direction, and (iii) the anatomical routing of multiarticular muscles makes co-contraction unavoidable for many tasks. Moreover, creating realistic and clinically useful finger models still requires developing new computational means to simulate the viscoelastic tendinous networks of the extensor mechanism, and the muscle–bone–ligament interactions in complex articulations. Building upon this neuromuscular biomechanics paradigm is of immense clinical relevance: it will be instrumental to the development of clinical treatments to preserve and restore manual ability in people suffering from neurological and orthopedic conditions. This understanding will also advance the design and control of robotic hands whose performance lags far behind that of their biological counterparts.

Keywords: Hand; Human; Manipulation; Muscle; EMG; Neural; Motor control; Robotics

1. Introduction

Static and dynamic manipulation of objects with the fingertips is essential to the activities of daily living. Manipulation ability is vulnerable to orthopedic/neurological disease and aging because it hinges upon the exquisite interaction between the complex anatomy of the hand and nervous system (Valero-Cuevas, 2000a). The restoration of manipulation ability is the subject of an entire medical field (Tubiana, 1981; MacKenzie and Iberall, 1994; Brand and Hollister, 1999; Green et al., 1999). In spite of these efforts, the legendary complexity of the hand has delayed a comprehensive understanding of biomechanical function and neuromuscular control of the hand.

Given that the neuro–musculo–skeletal complexity of the hand is not well understood, I have found it useful to define a conceptual paradigm to outline the fundamental neuro–musculo–skeletal components of the hand and their interactions (Valero-Cuevas, 2000a) (Fig. 1). Creating a fundamental understanding of manipulation necessitates an integrative paradigm firmly grounded on the mechanics of finger function, but equally devoted to anatomical detail and the meticulous characterization of

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doi:10.1016/j.jbiomech.2004.04.006

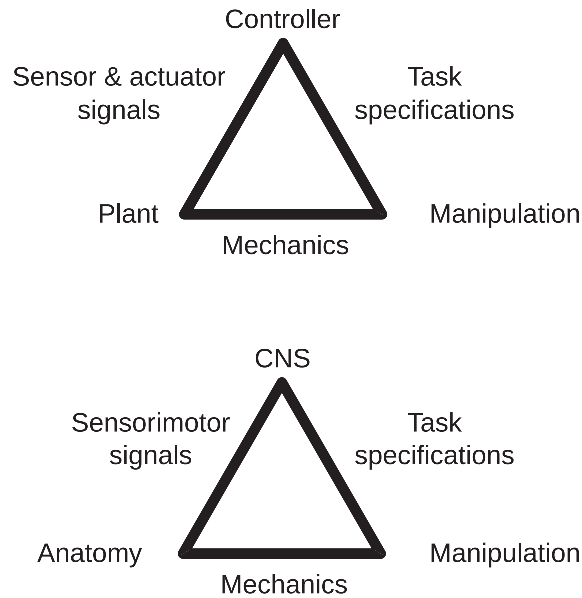

Fig. 1. Conceptual paradigm outlining fundamental neuro–musculo–skeletal components of the human hand and their interactions. For an electromechanical manipulator (Top), laws of mechanics define what grasping function a given manipulator (i.e., plant) can accomplish. Whether and how this function is realized depends on the ability of the controller to appropriately interpret task specifications and sensor signals, implement the appropriate control law, and send actuators signals to the plant. For a biomechanical system such as a human hand (Bottom), the anatomy (articulations, bones, sensory organs, muscles, etc) and central nervous system (CNS) are analogous to the plant and controller, respectively. Both machine and biological systems are part of the same continuum of solutions to the same mechanical challenge of manipulating objects. To date, our investigations have focused on how these fundamental neuro–musculo–skeletal elements of human fingers interact to produce static and dynamic fingertip forces for manipulation tasks such as precision pinch. We interpret ‘‘fingertip’’ loosely to mean the portion of the distal phalanx in contact with the object. (Adapted from Valero-Cuevas, 2000a.)

muscle activity. This paradigm has motivated me to pursue collaborative studies that combine principles of mechanics, anatomy and neurophysiology.

To understand the impairment and restoration of manipulation, I have begun by first comprehending the biomechanical requirements for static and dynamic precision pinch, and how the neuro–musculo–skeletal system meets those requirements. I refer to ‘‘static precision pinch’’ as the sensorimotor ability to regulate the magnitude and direction of the fingertip force/torque vectors in the absence of fingertip motion. ‘‘Dynamic precision pinch’’ also requires the regulation of finger motion (Murray et al., 1994; Valero-Cuevas et al., 1998; Valero-Cuevas et al., 2003b). For simplicity I use ‘‘finger’’ to mean any finger—including the thumb—unless otherwise specified, and ‘‘fingertip’’ as the portion of the tissue surrounding the distal phalanx in contact with the object manipulated. My focus on static and dynamic precision pinch is necessarily limited in that it does not yet address important issues such as neural and anatomical coupling among digits (Leijnse et al., 1993; Zatsiorsky et al., 1998; Latash et al., 2001; Li et al., 2001a; Keen and Fuglevand, 2003; Keen and Fuglevand, 2004a; Keen and Fuglevand, 2004b; Maas et al., 2004) or free finger motion (Cole and Abbs, 1986; Dennerlein et al., 1998b; Santello et al., 1998; Dennerlein et al., 1999; Sancho-Bru et al., 2001).

This overview of our work on the biomechanical function and neuromuscular control of the fingers is presented around three Research Themes: (I) Mechanics-based quantification of fingertip forces; (II) Anatomically realistic musculoskeletal finger models; and (III) Neural control of finger muscles.

2. Research Theme I: Mechanics-based quantification of fingertip forces

Using the scientific method requires that hypotheses be tested against experimental data. Therefore, a rigorous mechanics-based definition of finger function, and appropriate means to measure it, are prerequisites to progress in our clinical and scientific understanding of the biomechanical function and neuromuscular control of the fingers in manipulation. Roboticists, for example, have long been inspired and challenged by the functionality and versatility of the human hand—especially because its musculotendons are relatively sluggish actuators, nerve conduction velocities are much slower than electrical signals, and the musculature appears unnecessarily abundant. In their efforts to create comparably versatile robotic hands, they developed a mathematical framework to study the mechanical effectiveness of multifingered hands based on the function of their fundamental unit: the individual finger (Cutkosky, 1983; Murray et al., 1994). Effective precision pinch depends fundamentally on our ability to move and place the fingertips on an object, and to produce appropriate fingertip force and torque vectors (Cutkosky, 1983; Murray et al., 1994). In this Research Theme, we use a mechanical framework to find ways to define and measure the mechanical output of human fingertips as a necessary step to understanding multi-finger manipulation by the human hand.

From this mechanics perspective, human fingers are modeled as open serial kinematic chains of three rigid links with rotational degrees-of-freedom (DOFs) that allow control over the position and orientation DOFs of the distal phalanx (Fig. 2). The ‘‘Jacobian’’ matrix of this mechanism specifies the vector mapping from net torques at each DOF and fingertip forces/torques, and vice versa (Cutkosky, 1983; Murray et al., 1994). We have used these well-known relationships away from singularities to design experiments that unambiguously define the mechanical task specifications