# Preface

## Are Robot Hands Necessary?

As identified in the 2013 roadmap for US robotics, robotics is expected to impact society on a massive scale in the coming decades economically and socially in the manufacturing, healthcare, medical, and defense sectors. In addition to the traditional use of robots for automation in factories, recent advances in the human sciences have energized the field of robotics toward the development of personal robotic assistants and brain-machine interfaces for assisting the disabled. While great strides have been made in the areas of computer vision and autonomous navigation that have enabled autonomic robotic cars, one of the biggest drawbacks with robots so far is that they cannot accomplish physical interaction tasks in everyday settings. Specifically, robots cannot grasp and manipulate objects in unstructured environments, or environments for which they have not been designed. A lack of robotic hands that are capable of robust grasping and dexterous manipulation is holding back the robotics field. Thus, there is an increased interest to solve the robotic manipulation problem. The reasons for this deficiency are many, including the lack of robust hardware, primitive sensing methods, and a limited understanding of how to integrate sensory information and motor control.

*A key goal of the robotics community is to build robotic hands that can accomplish human grasping and manipulation tasks in human environments by physically interacting with humans and objects.* Such robot hands will have an immediate impact on applications such as teleoperated search-and-rescue operations, semi or fully autonomous robot applications (e.g., planetary rovers), rapidly reconfigurable manufacturing, and medical and healthcare operations. In addition to automating operations in these different fields, advances in robot hands will also advance upper-extremity prostheses. Note that the most popular prosthesis to date remains the single degree of freedom, body-powered split hook, because of its robustness and the human ability to learn how to use it. There have been significant advances in myoelectric prostheses, but challenges remain in providing control signals in an intuitive manner to control numerous degrees of freedom in more sophisticated prostheses.

## The Human Hand as Inspiration

The human hand has been the “gold standard” for robotic hand designers for decades. There are several reasons for this. First, the human hand exhibits tremendous dexterity and flexibility, and designers are keen to achieve such dexterity in robot hands. Second, everyday tools, objects, and environments are designed for use by a human hand (for example, where handles are placed on objects), and thus it is advantageous to mimic the human hand when designing robot hands to operate those same tools and objects in human environments. Third, the anthropomorphic form factor is highly relevant to prosthetic applications. Thus, most robot hand designs mimic the human hand.

However, the human hand is difficult to mimic since it is a complex system. In terms of “hardware,” the human hand contains 22 joints driven by nearly 38 muscles through a complex web of tendons. In addition, it has thousands of embedded sensors which provide information about posture, muscle and tendon forces, contact, interaction forces, vibration, and temperature. In terms of “software,” there are millions of neurons in the brain and the spinal cord that integrate information from the raw sensory signals before providing control signals through synergistic control inputs and reflex loops. Together, these different features enable the hand to perform a variety of dexterous tasks, but the roles that each component plays in different tasks is not entirely clear.

Roboticists want to understand what physical and computational features from the biological hand would benefit the design and control of highly capable robotic hands. This is the focus of this book. By bringing together the latest research on biological hands and the state-of-the-art in robotic hand technology in one book, we hope to inspire new ideas that will foster a deeper understanding of the human hand, accelerate the advancement of robotic hand research, and bridge multiple research communities through common interests in hands.

Note that some researchers are moving away from using the human hand as the template for robotic hands because of the difficulty in mimicking its compactness, form, and control. Specifically, they are designing “underactuated robotic hands” with many degrees of freedom but reduced number of actuators. These designs utilize tendon-driven systems or linkage mechanisms for creating movement and achieving human-like grasping capability. Such hands can surely address design criteria such as robustness and simplicity of sensing and control for static grasping. However, much work is still required to achieve human-like dexterity for manipulation.

## How this Book Came About

The idea for a book on human and robot hands arose during a workshop organized by Dr. Ravi Balasubramanian (coeditor of this book) and Dr. Yoky Matsuoka as part of the Robotics: Science and Systems conference in Seattle in 2009. The workshop was a forum for researchers to discuss the field of robotic grasping and manipulation viewed in relation to the human hand's capabilities, and to push the state-of-the-art in robot hand design and control. Topics discussed at the workshop included human hand biomechanics, neural control, sensory feedback and perception, and robotic grasp and manipulation. Over seventy researchers attended. Since no book existed that combined research on human and robot hands, it was decided to assemble a comprehensive work that discusses the latest developments in these fields by building on the workshop's proceedings. Dr. Veronica Santos joined as a co-editor due to her expertise in bioengineering.

## Book's Expected Audience

We expect that this book will benefit researchers from diverse areas such as robotics, biomechanics, bioengineering, neuroscience, and anthropologists. Together, these different fields can synergistically learn and apply each other's techniques to their problems. For example, the mathematical underpinnings of creating contact forces through a robot's motors can be applied to the analysis of using the hand's muscles to create fingertip forces. Integration of sensory data, reflex algorithms, and grasping strategies from humans can be used to develop advanced control algorithms for robots.

## Book Layout

The book is divided into two Parts. Part I focuses on the human hand's anatomical structure and function and the state-of-the-art methods that are used to derive insights into those aspects. Part II provides a broad perspective on the approaches for human-inspired robotic hand design and control. Brief descriptions of the chapters in each section are below.

## Part I: The Rich Complexity of the Human Hand and Its Control

The first four chapters of the book detail the neural control, kinematics, and musculotendon properties of the human hand as they relate to motion and force production capabilities. Chapter 1 by Schieber describes the cortical control of the human hand as a widely distributed network that can drive fixed synergies for grasping, act as diverse elements for individuated finger movements, and flexibly recombine elements for motor learning and reorganization after injury. Chapter 2 by Santello describes the phenomenon of common neural input as one of the mechanisms through which the central nervous system might coordinate the neural activation of groups of hand muscles acting on a single digit or multiple digits. Chapter 3 by Stillfried et al. explores the use of magnetic resonance imaging to determine the locations and axes of rotations of finger joints which can have significant impact on hand function. Chapter 4 by Lee and Kamper investigates the mechanisms of musculotendon force transmission such as finger posture, passive joint impedance, anatomical pulleys, and the tendon extensor hood for mapping muscle forces to index finger kinematics and dynamics.

The next three chapters discuss the characteristics and roles of tactile and proprioceptive sensory feedback mechanisms in the human hand. Chapter 5 by Jones presents the roles played by mechanoreceptors, or mechanical sensors, embedded in the human hand for the perception and control of finger forces. Chapter 6 by Walsh et al. describes the sense of proprioception with a focus on recent evidence that perception of posture can be affected by muscle contraction history, and that illusions of joint position and movement can be induced by simultaneous activation of slowly adapting and fast-adapting cutaneous receptors. Chapter 7 by Bensmaia and Helms Tillery reviews the combined roles of tactile and proprioceptive sensation in hand function, with a focus on the integration of multiple inputs to extract information about haptic interactions and to create somatosensory images for upper-limb neuroprosthetics.

The next two chapters address two ways in which sensory feedback is used: reactive control of fingertip forces, and active haptic perception. Chapter 8 by De Gregorio and Santos reviews how precision grip forces are affected by intrinsic object properties, anticipation, load direction, and sensory feedback, and then presents evidence that unexpected torque loads can elicit reactive, pulse-like increases in grip forces whose strength depends on orientation of the load relative to the hand. Chapter 9 by Tavakoli discusses how tactile feedback and kinesthetic feedback together influence the human ability to distinguish objects though haptic recognition of material and shape properties of objects.

Chapter 10 by Dollar discusses how human hands are used and presents classification and taxonomy schemes for grasping and manipulation behaviors based on hand-centric and motion-centric categorization. Such classifications of hand use can be applied to the fields of biomechanics, rehabilitation, prosthetics, and robotic manipulation.

## Part II: Human Hand-Inspired Robotic Hand Design and Control

Chapter 11 by Controzzi et al. provides a historical perspective about robotic hand design, including simple prostheses from the Roman times to highly advanced anthropomorphic robotic hands with a multitude of joints, sensors, and motors.

The next four chapters discuss the modeling of hand motion and force production using robotics techniques, with a focus on how anatomical structures like tendons and fingertip shape and compliance influence grasping capability. Specifically, Chap. 12 by Inouye et al. describes a novel, systematic approach to analyze and optimize tendon routing and pulley size for three-dimensional force production by a tendon-driven finger. Chapter 13 by Sueda and Pai provides a novel method for dynamically simulating human hand movement, while factoring in aspects such as the sliding of tendons over bones beneath the skin. Chapter 14 by Inoue and Hirai presents an analytical exploration into how hand compliance provides robustness to grasps even if there are significant delays in conveying control input through the biological neural system. Chapter 15 by Arimoto and Yoshida describes a method for computationally modeling the stability of “blind” multifinger grasps for which there is no tactile or visual information.

The next four chapters discuss the development of robotic hardware components: haptic devices that can apply forces to human fingertips, and tactile sensors which are critical for robotic hands to sense physical interactions with the external world. Specifically, Chap. 16 by Endo and Kawasaki present the design and control of multifinger haptic devices with the goal of understanding the perception of fingertip forces in the human hand. Chapter 17 by Buttolo and Hannaford describes devices for quantifying properties of multifinger haptic interaction such as hand stiffness in pen-like grasps and sensory thresholds of multifinger versus single finger haptic exploration. Chapter 18 by Cutkosky and Ulmen present the development of miniature tactile sensors that mimic the slowly adapting and fast-adapting tactile units in the human hand with the goal of achieving dynamic tactile sensing in robots. Chapter 19 by Wettels et al. describes the development and use of a deformable, multimodal, biomimetic tactile sensor that provides simultaneous sensing of contact forces, microvibrations, and temperature.

Chapters 20 and 21 discuss two examples of the development of complete robotic hand hardware. Specifically, Chap. 20 by Varol et al. describes the challenges in designing biomimetic transradial prostheses, particularly addressing the constraints of housing many actuators and sensors in the small volume of a human-sized hand. Chapter 21 by Deshpande and Matsuoka discuss the design and control of an “anatomically correct testbed” robotic hand, in which bone shapes and tendon routing within the human hand are mimicked.

The book concludes with three chapters that focus on developing advanced grasping and manipulation strategies for robots either by learning from humans or through physics-based modeling and computation. Chapter 22 by Balasubramanian et al. presents a novel experiment to identify human heuristics for grasping tasks and the use of those heuristics to improve automatic robotic grasping performance. Chapter 23 by Chang and Pollard explores the preparatory physical interactions humans have with objects prior to grasping an object with the goal of programming robots to exploit similar interactions to improve robotic grasping capability. Finally, Chap. 24 by Allen et al. presents a unique look at advancing robotic grasping by using massive computing power to identify appropriate grasps for previously unseen and incomplete shapes by drawing relationships to grasps achieved on well-defined training objects.

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