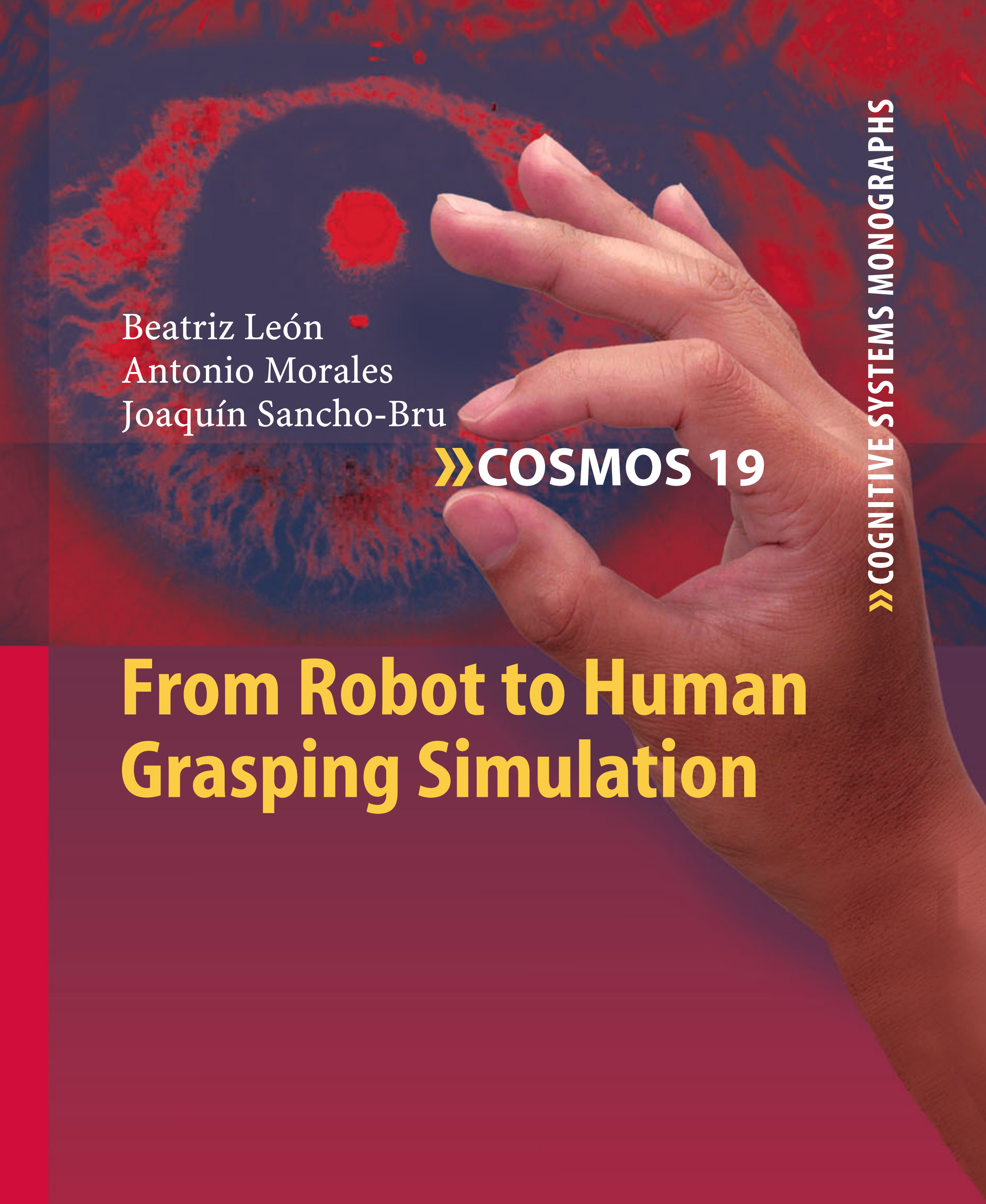

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From Robot to Human Grasping Simulation

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Preface

The human hand and its dexterity in grasping and manipulating objects are some of the hallmarks of the human species. For years, anatomic and biomechanical studies have deepened the understanding of the human hands' functioning and, in parallel, the robotics community has been working on the design of robotic hands capable of manipulating objects with a performance similar to that of the human hand. However, although many researchers have partially studied various aspects, to date there has been no comprehensive characterization of the human hands function for grasping and manipulation of everyday life objects.

Our hypothesis is that the confluence of both scientific fields, the biomechanical study of the human hand and the analysis of robotic manipulation of objects, greatly benefits and advances both disciplines. Additionally, we believe that the use of a simulation framework in which we could model and validate each of the processes involved in dexterous grasping is crucially important. Therefore, in this book, the current knowledge of robotics and biomechanics guides the design and implementation of a simulation framework focused on manipulation interactions that allows the study of the grasp through simulation.

In the first part of this book, we detail *OpenGRASP*, a simulation engine focused on robot manipulation interactions embedded in a real grasping cognitive system. Tactile sensor simulation is studied in detail, resulting in a new tactile sensor model. Several applications of the simulator in robot grasping are presented, demonstrating how grasp simulation is a key tool for constructing a world model and understanding the robots environment. Additionally, we demonstrate how to achieve a complete dynamic simulation of a humanoid robot.

In the second part, we use the knowledge acquired from robot simulation to create *OpenHand*, a simulation engine that provides a more comprehensive model of the human hand focused on object grasping and manipulation. It provides a realistic biomechanical hand model of the skeleton, muscles and tendons, including the simulation of the skin and the neuromuscular control. Additionally, it includes tools for grasp analysis such as mechanical contact modelling and control algorithms for closing the hand. We show an application of how the simulation can be used to solve the indeterminate problem of finding the muscular forces that ensures the equilibrium of the grasped object, by minimising different objective functions. Moreover, we propose different quality measures to evaluate various aspects of the human grasps by adapting existing robotic metrics and proposing new measures that consider its biomechanical characteristics, such as muscular fatigue. Finally, the knowledge acquired from the evaluation of grasping in humans is compared with grasping performed by a prosthetic hand demonstrating how the gap between robot and human grasp manipulation could be reduced.

As a result, a valuable framework for the study of the grasp, with relevant applications in several fields such as robotics, biomechanics, ergonomics, rehabilitation and medicine, has been made available to these communities.

Castellón de la Plana
July 2013

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Part II Human Grasping Simulation

Chapter 1
Introduction

The human hand and its dexterity in grasping and manipulating objects are some of the hallmarks of the human species. Most of human mechanical interactions with the surrounding world are performed by the hands. We use our hands to perform very different tasks; from exerting high forces (e.g. using a hammer or helping each other carry heavy things) to executing very precise movements (e.g. cutting with a surgical tool or playing an instrument). We also use them to express our feelings, utilising them as a dominant part of our body language. This versatility is possible because of a very complex constitution: a great number of bones connected through different joints, a complicated musculature and a dense nervous system. This complexity is already evident from the kinematics point of view, with more than 23 degrees of freedom [1] controlled by muscles, tendons and ligaments.

For years, anatomic and biomechanical studies have deepened the understanding of their structure, functioning and limitations. There has been an extensive scientific contribution describing and modelling individual components of the human hand: its mechanical structure, the muscular function, the nerve network, mechanical and sensory properties of skin, cognitive functions of manipulation, and many other aspects. However, although many researchers have partially studied various aspects of the human hand from the neuro-physiological and biomechanical viewpoints, to date there has been no comprehensive characterization of the human hand function for grasping and manipulating of everyday life objects, mainly because of the lack of a sufficiently detailed and accurate tool for its simulation.

In parallel, in the field of robotics, the increasing demand for robotic applications in dynamic and unstructured environments and novel situations is motivating the need for dexterous robot hands and grasping abilities, which can cope with the wide variety of tasks and objects encountered in such environments. The scientific community has been working extensively on the design and construction of robotic hands and in all aspects of their control. The explicit goal of these studies is to endow robots with hands capable of manipulating objects with a performance similar to that of the human hand. Although the state of the art in robotics is still far from achieving this purpose, an important body of theoretical and practical knowledge on manipulation

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has been created. Of particular relevance are the advances in the mechanical and mathematical modelling of the interactions between objects, which is a fundamental aspect in the analysis of robotic manipulation.

Our hypothesis is that the confluence of both scientific fields, the biomechanical study of the human hand and the analysis of robotic manipulation of objects, can be a breakthrough in the development of both disciplines. On one hand, the biomechanical study of the human hand is enriched with mathematical analysis techniques to manipulate objects, and on the other the design of robotic hands would benefit from a better understanding of the functioning of the human hand.

1.1 The Grasping Process

Grasping is a core cognitive capability and has been considered as one of the key factors of the evolution of the human brain [2]. In the grasping and manipulation process we can distinguish three main phases: approaching, grasping and manipulating the object. During the approaching phase, the arm moves towards the object and the fingers perform an initial opening to accommodate the object. Subsequently, during the grasping phase, the fingers close to make contact with the object and press it and then the arm and wrist perform the corresponding movements to overcome external forces or torques during the grasp, producing small adjustments in the position of the fingers. Finally, during the manipulation phase, if the task requires changes in the contact points for manipulating the object, coordinated changes are performed in the finger's pressure or position in order to perform such a task without losing the stability of the object. The use of the senses of sight and touch—coordinated by the central nervous system—in the entire process, is critical to the grasp success and efficiency.

Recent works in the grasping literature have different approaches depending on the objectives of the particular study or the researchers' background. Thus, there are papers that focus on analyzing the gripping process from the neurophysiological point of view [3–6], others from the point of view of biomechanics [7–10], while others seek to transfer ideas for robotic manipulators' grip [11–13], some explore the use of other tools [14] and others from the clinical point of view [15, 16].

1.1.1 Grasping in Biomechanics

Mathematical representations, known as biomechanical models of the hand, are used in order to perform qualitative or quantitative analyses on this complex reality. In biomechanics, their use allows studying problems that cannot be analysed directly on humans or that have an experimental cost that is too high; e.g., the study of new alternatives for restoring hand pathologies. Biomechanical models are a description of the hand as a mechanical device: the different elements of the hand are defined in terms of rigid bodies, joints and actuators, and the mechanical laws are applied.

As they are simplified mathematical models of the reality, their use and validity depends on the simplifications considered.

The first biomechanical models of the hand were developed to explain and clarify the functionality of different anatomical elements. In this regard, we can find many works that studied the function of the intrinsic muscles [17–22], others that tried to give an insight into the movement coordination of the interphalangeal joints [23, 24] or studying the causes and effects of different pathologies of the hand [20, 21, 25]. All these models were, however, very limited two-dimensional models allowing only the study of flexion-extension movements, they modelled only one finger, and they included important simplifications. By the year 2000, few three-dimensional models had been developed [26, 27], and none of them modelled the complete hand.

Since 2000, many three-dimensional biomechanical models can be found in literature, having been developed for very different purposes [28–43]: to understand the role of the different anatomical elements, to understand the causes and effects of pathologies, to simulate neuromuscular abnormalities, to plan rehabilitation, to simulate tendon transfer and joint replacement surgeries, to analyse the energetics of human movement and athletic performance, to design prosthetics and biomedical implants, to design functional electric stimulation controllers, to name a few.

All the effort in biomechanics has been focused on appropriately modelling the different hand components (kinematics, muscles, tendons, etc.). Little effort has been spent on the formulation of the grasping problem when using a biomechanical model. In this sense, many limitations persist. Current models do not allow the estimation of the contact information required to use biomechanical models for simulating the grasping of objects. Forces and zones of contact still need to be measured experimentally and input to the model.

In contrast, much research has been carried out on animation techniques over the past years, mainly for use in developing computer games. Lately, these advances have been cleverly used by some ergonomics researchers to develop improved graphical and kinematics hand models for evaluating the use of products [44–47], with good results.

1.1.2 Grasping in Robotics

The phases of human grasping have their counterparts in robotics, although differences in the manipulators dexterity and the available sensory information (visual or tactile) give robotic grasping its own particularities. Grasp planning for robotic multi-finger hands, as well as their dexterous manipulation, are challenging areas of research because of the difficulty posed by the high dimensionality of the configuration space of these manipulators. Besides the hand's internal degrees of freedom, the six degrees of freedom of the arm should also be considered. These describe the position and relative orientation between the object and the robot hand. In fact, despite the effort made over the past decades, there are no robotic hands that can fully emulate the kinematics of the human hand. One of the reasons is the 'hardware': human hands have five soft fingers with high dexterity and compliance compared to less dexterous robot hands featuring very simple contact surfaces. Apart from the hands, compared to humans, robotic arms also have less dexterity and flexibility. For these reasons and also because of the difficulty involved in grasp planning, researchers use robotic hands with few degrees of freedom and employing few predefined grasp preshapes [48].

Miller et al. [49] have predefined grasp preshapes for the Barrett hand with four degrees of freedom and have used primitives to generate the starting positions and directions of the robot hand in planning the grasps. Also, grasp quality measures have also been established [50] to objectively select the best among a predetermined set of grasps. Other researchers [51] have measured the quality of the orientation for the manipulation task to qualify the precomputed grasp.

Another important area of grasp research is focused on finding the location of contact points on the surface of the objects to maximize a certain grasp metric [52, 53]; however, it is difficult to adjust these contact points to feasible manipulator's configurations that are reachable by the robot and avoiding collisions with the environment.

Regarding grasp planning, traditional approaches for controlling robotic hands are typically discarded because they consider each finger as a separate kinematic chain. In these techniques, knowing the object to be grasped and the hand's initial position, the controller synthesizes the desired trajectory of each phalanx in order to complete the grip. Despite the difficulty of this type of control approach, this method was used to control the hand Utah-MIT [54] that is one of the most complex robotic hands that has been produced, with 16 degrees of freedom (4 fingers with 4 finger joints, with tendons emulated by wires) and a separate control for each phalanx.

There are different studies that have tried to plan robotic grasps through imitation or learning by demonstration [55–57]. It is difficult to apply algorithms to learn and imitate the movements of the human hand and translate them to the robotic grasp mainly because robot manipulators have very different kinematics and sensing capabilities with respect to the human hand. In general, motion planning for grasping is performed by simplifying the descriptions of the hand, the object and the task. When using neural networks and knowledge-based systems, a precise representation of the fingers' kinematics is not required [58].

In summary, the planning of robotic grasp for multi-finger hands has been focused on the study of the physical properties of a given grasp or the computation of grasps that meet certain desirable properties. These algorithms use different metrics to determine the quality of the grasps, unlike what happens in the field of the grasping in biomechanics. However, these approaches have failed to deliver practical implementations for a number of reasons, the most crucial being that the methods mostly rely on assumptions that are not satisfied in complex environments with a high degree of uncertainty. Additionally, the grasps studied in robotics are dependent on the characteristics of the robotic hands, and very limited compared with the human hand. Some studies use the learning from demonstration to track the human hand movements, and in the case of using human hand models, they suffer from realism in so far as they greatly simplify its degrees of freedom.

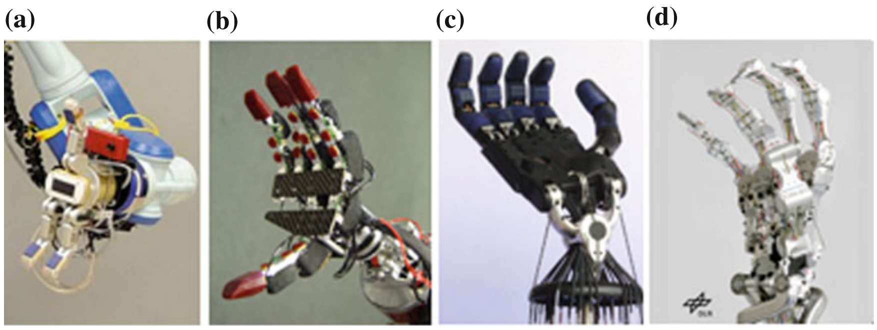

Fig. 1.1 Anthropomorphic robot hands: **a** Barrett Hand (courtesy of the UJI Robotics Intelligent Lab); **b** ARMAR III Hand (courtesy of the Institute for Anthropomatics at KIT); **c** Shadow Hand C5 (courtesy of Shadow Robot Company); **d** Anthropomorphic DLR Hand Arm System (courtesy of DLR Robotics and Mechatronics Centre)

In light of the proliferation of robotic hands (Fig. 1.1) that are becoming increasingly complex and similar to the human hand [59], the field of robotic planning will increasingly be associated with the study of human handling, especially in the area of service robotics where the robot should move in a human environment and manipulate common objects of daily living.

1.2 Simulation: A Tool Towards Understanding the Grasping Process

As we have seen, even with the recent advances in biomechanics and robotics, we have not been able to fully understand or, and to an even lesser degree, able to replicate the process carried out by humans that combines in a natural way: perception, action and predictive capabilities of achieving, mentally planning and then executing a grasp.

There are several questions that still need to be answered, for example: How is the human cognitive system able to plan and control complex manipulation tasks? How does it choose an specific grasp between an infinite set to perform a specific task for a given object? How does the central nervous system select and control the necessary strength required in each muscle to perform the chosen grasp and to counteract the external forces? How are we, from infancy, able to use our experience to learn and refine our capacity for grasping and manipulation?

The difficulty lies in the fact that there are several complex processes and systems involved which interact when humans perform dexterous grasping. First, there is the complex human cognitive system that processes sensory information and controls muscle activity. Second, we have a manipulator as complex as the human hand and arm, which has a highly sensitive sense of touch through the skin, deformable and compliant fingers able to produce soft contacts, more than 20 degrees of freedom, and a complex system of muscles, tendons and ligaments able to move them.

Finally, an environment governed by complex physical laws that characterize the behaviour of all objects within it.

In order to bring us closer to a comprehensive understanding of the human grasp, we believe that the use of a simulation framework in which we could model and validate each of these processes is crucially important.

Therefore, in this book we aim to lay the foundations for such a framework that allows the study of the grasp through simulation. This framework should allow, on the one hand, studying the human grasp and transferring this knowledge to several fields including robotics, medicine and rehabilitation. Furthermore, it should also enable us to study and improve robotic grasping with a system that would be capable, not only of replacing the real hardware, but, more importantly, of being part of the robot's cognitive system, acting as a prediction engine able to emulate the retrieval of self knowledge.

1.3 From Robot to Human Grasping Simulation

In this book, the current knowledge of robotics and biomechanics is used to draw out the rules for developing a simulation framework focused on manipulation interactions that provides the scientific community with a modular, flexible, and accurate tool. The validation and usefulness of the developed framework are shown through a wide set of practical applications.

The objective is two-fold: create a simulation framework that enables us (i) to predict the consequences of a robot grasp and to measure the performance after the execution and (ii) to evaluate the human grasp to achieve a better understanding of the human hand which will help us to transfer this knowledge to the robot's field. *Framework for Grasping Simulation* consists of two parts:

1. **OpenGRASP: A Framework for Robot Grasping Simulation**. A simulation engine focused on robot manipulation interactions embedded in a real grasping cognitive system. This simulation engine enables the system to store and manipulate abstract and specific representations of the perceived objects; to consider possible actions; to predict the results and to plan sequences of actions that complete a desired goal accordingly; to make hypotheses about the real properties of the world; and, finally, to react when an unexpected behaviour occurs. It provides the possibility to develop a grasp reasoning engine including an introspection framework, making its role central in the understanding of human activities and planning new manipulation actions.
2. **OpenHand: A Framework for Human Grasping Simulation**. A simulation engine aiming to obtain a more comprehensive model of the human hand focused on object grasping and manipulation, integrating knowledge and developments from the fields of biomechanics, ergonomics, robotics, and computer animation. It provides a realistic biomechanical hand model of the skeleton, muscles and tendons, including the simulation of the skin and the neuromuscular control.

Additionally, it includes tools for grasp analysis such as mechanical contact modelling, control algorithms for closing the hand and development and application of grasp quality metrics.

The research presented in this book aims to advance the understanding of robot and human grasp, producing a broad set of potential applications of its results. From the society's point of view, it can enhance the capabilities of surgeons for surgical planning in hand operations and open ways to obtaining better bionic limbs that can improve the lives of amputees and the disabled. From the economic point of view, these lines of work could have important medium to long-term implications by opening more possibilities in the field of service robotics to improve grasping capabilities thanks to a better understanding of the hand's functioning, which could result in the development of companies in this sector. From the industrial point of view improving multiple-finger manipulators can enable automation of industrial processes assembly currently being performed manually.

The work proposed herein should be considered as the initial stage in the development of a comprehensive framework for grasping simulation that in the future would consolidate the results obtained in different areas of multidisciplinary knowledge. Therefore a dormant target, but no less important, will be to identify gaps that still exist in the scientific literature for building more challenging future proposals.

1.4 Outline

The book is divided in two main parts. The first one, composed of Chaps. 2 to 4, is devoted to explaining the contributions of robot grasping simulation, while the second, Chaps. 5 to 7, details the evaluation of human grasping using simulation. More precisely, the book is structured as follows.

1.4.1 Part I: Robot Grasping Simulation

Chapter 2: *Robot Grasping Foundations* Introduces the foundation of this book, presenting the basic concepts and definitions involved in the study of object grasping and manipulation tackled in the following chapters.

Chapter 3: *Robot Grasping Simulation* The chapter introduces OpenGRASP, the developed simulation toolkit for grasping and dexterous manipulation, presenting its different components. Tactile sensor simulation is studied in detail, proposing a new tactile sensor model which utilizes collision detection and response methods using soft contacts as well as a full friction description.

Chapter 4: *Applications of Robot Grasping Simulation* In this chapter, the applications of the developed simulator in robot grasping are presented. It is demonstrated how grasp simulation is a key tool for constructing a world model and understanding the robot's environment. Additionally, we demonstrate how to achieve a complete dynamic simulation of a humanoid robot using the developed toolkit.

1.4.2 Part II: Human Grasping Simulation

Chapter 5: *Human Hand Model* This chapter presents a review of the literature regarding biomechanical and ergonomics hand models. The current knowledge on hand models is used to draw out the rules for developing a realistic and self-contained biomechanical model of the hand with special emphasis on grasp and object manipulation. The proposed model consists of a scalable biomechanical model of the human hand composed of bones, tendons, muscles and skin. On this basis, we added closure algorithms to grasp virtual objects, contact models, which allow estimating the transmission of forces in the contacts, and quality indices to provide grasp evaluation tools.

Chapter 6: *Human Grasp Evaluation* This chapter presents a review of the grasp quality measures that have been proposed and then the adaptation of the most common robotic grasp quality measures to the human hand grasp evaluation. Additionally, it presents the proposal of complementary quality indices that may consider biomechanical aspects not taken into account by the robotic indices.

Chapter 7: *Human Grasping Simulation* This chapter presents a study of the adapted grasp quality measures presented in the previous chapter to find the minimum set of indices that enable the evaluation of the different aspects of the human grasp on simulation. Moreover, we present a proposal to calculate a global grasp quality index combining the independent grasp aspects. Finally, the framework for grasp evaluation is used to compare the grasp capabilities of a prosthetic hand with the ones obtained with our human hand model.

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Part I
Robot Grasping Simulation

Chapter 2
Robot Grasping Foundations

2.1 Introduction

In this book, we focus on the grasping problem, consisting of determining the grasp required to carry out certain manipulation tasks on an object.

Definition 2.1 A *grasp* is commonly defined as a set of contacts on the surface of the object, which purpose is to constrain the potential movements of the object in the event of external disturbances [1–4].

For a specific robotic hand, different grasp types are planned and analysed in order to decide which one to execute. A contact model should be defined to determine the forces or torques that the robot manipulator must exert on the contact areas. Most of the work in robotics assume point contacts, and larger areas of contact are usually discretized to follow this assumption [2]. Two main problems can be distinguished in robotic grasping: analysis and synthesis [5].

Definition 2.2 *Grasp analysis* consists on finding whether the grasp is stable using common closure properties, given an object and a set of contacts. Then, quality measures can be evaluated in order to enable the robot to select the best grasp to execute.

Definition 2.3 *Grasp synthesis* is the problem of finding a suitable set of contacts given an object and some constraints on the allowable contacts.

In the following sections, a detailed description of the contact models and the most common approaches for grasp analysis and synthesis are presented. The definitions of the terminology and notation are mainly taken from [3, 6] where the reader is referred to find a complete overview of the modelling of contact interfaces and an introduction of the fundamental models of grasp analysis.

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Table 2.1 Notations

$\{W\}$	Word coordinate frame
$\{O\}$	Object coordinate frame
n_c	Number of contact points
c_i	Contact point i relative to $\{W\}$
$\{C\}_i$	Contact point i coordinate frame with axis $\{\hat{n}_i, \hat{t}_i, \hat{o}_i\}$
$\hat{n}_i$	Unit normal to the contact tangent plane directed toward the object
p	Position of the object relative to $\{W\}$
v	Linear velocity of point p
ω	Angular velocity of the object relative to $\{W\}$
w_i	Generalized force acting on the object for a unit force along $\hat{n}_i$
f_i	Force applied to the object at the point c_i
τ_i	Resulting moment at point p
w_o	Total set of wrenches that can be transmitted to the object through the n_c
w_{ext}	Disturbing external wrenches
μ	Friction coefficient of the contacting materials
β	Half-angle of the friction cone
m	Number of faces of discretized friction cone
B	Selection matrix
l	Total number of twist components transmitted
G	Grasp matrix
$\tilde{G}_i$	Partial grasp matrix
$\tilde{G}$	Complete grasp matrix
J	Hand Jacobian matrix
$\tilde{J}_i$	Partial hand Jacobian matrix
$\tilde{J}$	Complete hand Jacobian matrix
G_J	Grasp Jacobian matrix

2.2 Contact Modelling

2.2.1 Contact Kinematics

Consider a manipulator contacting a rigid body whose position and orientation is specified by the location of the origin of a coordinate frame $\{O\}$ fixed to the object and the orientation of this coordinate frame relative to an inertial frame $\{W\}$ fixed in the world (see Fig. 2.1). Let $p \in \mathbb{R}^3$ be the position of the object and $c_i \in \mathbb{R}^3$ the location of a contact point i relative to $\{W\}$. At this contact point, we define a frame $\{C\}_i$ with axis $\{\hat{n}_i, \hat{t}_i, \hat{o}_i\}$ where $\hat{n}_i$ is the unit normal to the contact tangent plane and is directed toward the object. The other two unit vectors are orthogonal and lie in the tangent plane of the contact. For readers' convenience, a list of notations is given in Table 2.1.

Definition 2.4 A *twist* is the representation of the spacial velocity of the object and can be written as $t \in \mathbb{R}^6$: