Towards a Realistic and Self-Contained Biomechanical Model of the Hand

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1. Introduction

Most of human mechanical interactions with the surrounding world are performed by the hands. They allow us to perform very different tasks; from exerting high forces (e.g. using a hammer) to executing very precise movements (e.g. cutting with a surgical tool). 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 20 degrees of freedom (DOF) controlled by muscles, tendons and ligaments.

Mathematical representations are used in order to perform qualitative or quantitative analyses on this complex reality. These representations are known as biomechanical models of the hand. 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 (Leijnse & Kalker, 1995; Spoor, 1983; Spoor & Landsmeer, 1976; Storace & Wolf, 1979, 1982; Thomas et al., 1968) and many others that tried to give an insight into the movement coordination of the interphalangeal joints (Buchner et al., 1988; Lee & Rim, 1990). Models for studying the causes and effects of different pathologies of the hand also appeared early on, such as the swan neck and boutonnière deformities or the rupture of the triangular ligament or the volar displacement of the extensor tendon (Smith et al., 1964; Storace & Wolf, 1979, 1982). All these models were, though, 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 (Biryukova & Yourovskaya, 1994; Casolo & Lorenzi,

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1994; Chao et al., 1976; Chao & An, 1978; Esteki & Mansour, 1997; Mansour et al., 1994; Valero-Cuevas et al., 1998), 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 (Fok & Chou, 2010; Kamper et al., 2006; Kurita et al., 2009; Lee et al., 2008a, 2008b; Qiu et al., 2009; Roloff et al., 2006; Sancho-Bru et al., 2001, 2003a, 2003b, 2008; Valero-Cuevas, 2000; Valero-Cuevas et al., 2000, 2005; Vigouroux et al., 2006, 2008; Wu et al., 2010): 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. These models, however, do not differ much from the ones developed before 2000, and many limitations are still evident. For example, contact forces and zones 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 (Endo et al., 2007, 2009; Goussous, 2007; Kawaguchi, 2009), with good results.

On the other hand, robot hand grasps have been extensively studied for years. Although until 2000 little attention was paid to human hand grasping, this too has become a hot topic in robotics. The experience in modelling the robot hand grasps has been used to reach a better understanding of human grasping (Miller & Allen, 2004; Peña-Pitarch, 2007). The hand is considered as the end-effector for humans. These models, however, are not appropriate for studying many of the above-mentioned objectives, as their interest is different. The focus in robotics research is on planning the grasp and finding an optimum grasp, and quality grasp measures that have been developed for robots are used. These models do not include muscles and tendons in the formulation.

The latest developments in ergonomic hand models and human hand grasp models can be used to improve the existing biomechanical models of the hand and extend their functionality. A promising research area lies ahead with scientist, aiming to obtain a more comprehensive model of the hand, integrating knowledge and developments from the fields of biomechanics, ergonomics, robotics, and computer animation.

In this chapter, a review of the literature regarding biomechanical models of the hand, ergonomics hand models and human hand grasp models is presented. The three approaches are used to draw out the rules for developing an improved biomechanical model, able to tackle any of the above-mentioned objectives in a virtual environment, without external experimental data.

2. Literature review

2.1 Biomechanical models of the hand

Over the years, biomechanical models of the hand have been developed for different purposes. Some of them tried to study the functionality of different anatomical elements with the aim of gaining a deeper understanding of the causes and effects of many hand pathologies. These are usually very simplified (mostly two-dimensional) kinematic models (sometimes dynamic) that are used to perform qualitative analyses (Leijnse et al., 1992;

Storace & Wolf, 1979). Others were developed to help in medical planning and surgery for patients; they are usually dynamic models and are used to perform quantitative analyses, such as the study of the tendon excursions in the medical planning of tendon transfers (Giurintano & Hollister, 1991) or to study the nervous stimulation required to restore the grasping ability in muscular dysfunction patients (Esteki & Mansour, 1997). Yet others studied the hand while performing specific tasks with different aims, so as to have approximate values for the articular forces for testing prosthetic designs (Weightman & Amis, 1982). These too are quantitative analyses performed on dynamic models.

Recent models do not differ much from the ones developed before 2000 (Fok & Chou, 2010; Kamper et al., 2006; Kurita et al., 2009; Lee et al., 2008a, 2008b; Qiu et al., 2009; Roloff et al., 2006; Sancho-Bru et al., 2001, 2003a, 2003b, 2008; Valero-Cuevas, 2000; Valero-Cuevas et al., 2000, 2005; Vigouroux et al., 2006, 2008; Wu et al., 2010). All models present a similar configuration. The kinematics are modelled without considering the restraining structure, just the resultant physiological articular movement. The concept of instantaneous centre of rotation has been used to define an axis of rotation in joints with a single predominant DOF. Much effort has also been spent on finding the rotation axes of joints with two DOF (Brand & Hollister, 1992), through the consideration of a virtual link connecting the axes (Giurintano et al., 1995). Thus, all works use fixed axes of rotation; depending on the joint, one or two axes of rotation are considered. This approximation has been found to be good enough for most of the cases, particularly if there is no interest in analysing the role of the articular soft tissue or the articular stresses (Youm et al., 1978).

All works in the literature consider the ideal case of a non-friction belt around a pulley to model the tendons on a joint. Therefore, the tensional force on a tendon is the same along its pathway if no split or connection to other tendon exists. Two different approaches have been used to model tendon action on the joints. The first one considers the tendon freely running when crossing the joint between two points attached one to the proximal segment of the joint and the other to the distal segment. This approach is the basis of the first serious attempt to develop a 3D normative model of the hand (An et al., 1979), in which the position of the tendons with respect the bone segments were obtained from the measurement on 10 fresh cadaveric specimens. The second approach comes from the application of the virtual work principle and considers the moment arm created by the tendon as the first derivative of the tendon excursion with respect to the rotated angle about the rotation axis under study (Storace & Wolf, 1979). This second approach is not strictly correct (Casolo & Lorenzi, 1994), as it does not take into account the work due to the deformation of the sheaths and other structures that constrain the tendon's trajectory along its pathway. Although both approaches present advantages and disadvantages, the second one is difficult to implement in 3D modelling, mainly because of the complexity in the tendon excursion calculation at joints with more than one DOF.

Most of the works in the literature use Hill's model to account for the muscles' mathematical modelling. This simple model allows the consideration of the three main parameters, i.e., muscle activation level and variation of the maximum deliverable muscle force with muscle length and muscle contraction velocity.

Finally, the dynamic equilibrium equations lead to an indeterminate system of equations, with more unknowns (muscle forces) than available equations. Inequality constraints taking into account the maximal forces that may be delivered by each muscle and that tendons cannot support compressive forces have to be considered as well. The problem is usually solved by minimising some cost function. Different functions have been investigated, most

of them without any physiological basis. The most often used criterion is the minimisation of the sum of the squared muscle stresses, which has been related to the maximisation of fatigue resistance (Crowninshield & Brand, 1981).

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.

2.2 Hand models in ergonomics

Ergonomics, according to the International Ergonomics Association, is 'the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimise human well-being and overall system performance'. Hand models in Ergonomics are used to simulate postures adopted while grasping objects with different purposes. One of the main goals of physical ergonomics is the study of the size and shape of objects according to the anthropometry of the different people that have to interact with them. Thus, the main feature of a model for Ergonomics is that it has to allow representing different populations and percentiles. People having hands of different sizes and proportions will adopt different postures in grasping the same object for the same functions. For example, pressing a button of a phone with the thumb while holding it with the same hand can be easily achieved for a specific hand size while keeping the grasp. However, other people with different size of hand will need to change the grasping posture to achieve pressing the button. This is a typical problem of reach that needs to be solved in ergonomic assessment.

In recent years, virtual humans have been incorporated into the design process for ergonomic assessment of different types of products, mainly in the aerospace and automotive industry but also in others like product design, tasks simulation, personnel training or simulation of other worker environments (Colombo & Cugini, 2005; Yang et al., 2007). Several commercial software programs such as Jack, RAMSIS, HumanCAD, Safework and SantosHuman are available and other studies have been conducted on digital human models such as SAMMIE (Case et al. 1990) or the Boeing Human Modeling System for the same purposes. A virtual human in these packages is defined as a kinematic chain composed of a number of rigid links connected by joints. These joints have the DOF and allowable motion limits corresponding to the anatomical joint of the human being. Direct and inverse kinematics is incorporated into the models so they can replicate human body movements and also evaluate forces acting in joints. Moreover, different population and percentiles may be selected for the size of the model, usually from known anthropometric databases. With these capabilities the problems of reach and clearance usual in ergonomics may be solved easily. Other useful capabilities of these models are the simulation of the sense of sight with virtual cameras located in the eyes or the possibility to change any particular data of the model, like dimensions of limbs or motion limits of some joints, in order to simulate a particular person or disability. However, the majority of these models focuses on the whole body and does not pay attention to the accuracy of the hand model. Most of them just incorporate a list of hand postures (grasping or others) to be chosen, i.e.

direct kinematics, but do not allow for example inverse kinematics for the joints of the hand, even when it is incorporated for the other joints of the body. In recent developments some attempts to improve the hand model incorporated into some programs have been done (Peña-Pitarch, 2007, Yang et al., 2007).

Early models of the hand (Davidoff & Freivalds, 1993) were actually kinematic models that simulated roughly the external geometry of the hand and its movements. The geometry of the hand has been modelled mainly by jointed cylinders (Fig. 1) and cones (Armstrong, 2009; Sancho-Bru et al., 2003a, 2003b). However, if the geometry of the hand model is not very accurate, the algorithms for inverse kinematics are not precise enough. Recently, some efforts have been made in accurately modelling the surface of real hands to be incorporated into 3D hand models. Rhee et al. (2006) presented an automated method to make a specific human hand model from an image of the palm of the hand. Different algorithms were used in the process: principal creases are extracted, joint locations are estimated from them and the skin geometry of a generic hand model deformed based on hand contours. Rogers et al (2008) made a scalable 3-D geometric model of the hand based on 66 landmarks of the palm surface from 100 subjects in four functional postures. The purpose was to analyse the deformation of the palm surface during the grasp of an object. Recent models incorporate the surface of the hand as a mesh object with more or less realism, obtained from the location of a number of landmarks of the hand or from digital 3D-scanning of the hand (Endo et al., 2007; Peña-Pitarch, 2007, van Nierop et al., 2008). The mesh is linked to a skeleton whose movement controls the deformation of the mesh with different types of algorithms.

Fig. 1. Different views of the geometric model used in Sancho-Bru et al. (2003a) simulating a hand gripping two cylinders of different diameters.

Other important aspect of hand models for ergonomics is associated with the study of musculoskeletal disorders. Early epidemiological studies (Mital and Kilbom, 1992) showed that the use of hand tools with an improper design for the worker or the task could lead to a high risk of developing cumulative hand trauma disorders (CHTD). The factors influencing the development of CHTD have been reported in different works (Keyserling, 2000; Kong et al., 2006; Muggleton et al., 1999; Schoenmarklin et al., 1994; Spielholz et al., 2001) and different methods have been used in these studies: epidemiological studies, physiological measurements (electromyography activity, pressure in tissues, posture of hand and wrist, tactile sensitivity), biomechanical models of hand and wrist structures and psychophysical assessments. These studies report that CHTD are associated with repetitive tasks, high forces, extreme or awkward postures of hand and wrist, velocity and acceleration of wrist motions and exposure time, among others. Different theories of injury development have been proposed (Kumar, 2001). All of them assume that CHTD and other musculoskeletal disorders are of biomechanical nature.

Therefore, biomechanical hand models able to predict movements, postures and internal forces of hand and wrist structures can be used to assess the risk of developing CHTD. Tendon excursions or maximum gripping strength have been used as index in different works to assess gripping posture for health (Armstrong et al., 2009, Sancho-Bru et al., 2003b).

None of the reported biomechanical models of the hand for ergonomics accounts for all the above-mentioned requirements, although some attempts have been made. Armstrong et al (2009) have developed a scalable kinematic model of the hand with simple geometry (cones and cylinders). The model includes a posture prediction algorithm for fingers that reproduces in a high percentage the observed postures and is able to compute tendon excursions and wrist movements. The model is used to assess how much space is required for hands in an assembly task and to calculate the risk of CHTD from tendon forces and hand strength. Other group of researchers (Endo et al 2007, 2009; Kawaguchi et al., 2009) have developed a scalable digital hand model with an accurate shape of the hand that includes a semiautomatic grasp planning function with robotics indexes of quality (see next section). The model incorporates a 'comfort database' obtained from experimental measurements to assess comfort of postures and is used in the assessment of physical interaction with electronic appliances.

2.3 Grasping in robotics

For many years the robotics community has been studying the autonomous handling of objects by robots. A robot should be able to locate the object and then grasp it, and possibly transport it to a specified destination. The purpose of a grasp is to constrain the potential movements of the object in the event of external disturbances. For a specific robotic hand, different grasp types are planned and analysed in order to decide which one to execute.

A grasp is commonly defined as a set of contacts on the surface of the object. 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 assumes point contacts, and larger areas of contact are usually discretised to follow this assumption (Bicchi & Kumar, 2000).

Two main problems can be distinguished in robotic grasping: analysis and synthesis (Mason, 2001). Grasp analysis consists on finding whether the grasp is stable using common closure properties, given an object and a set of contacts. Then, a quality measure can be evaluated in order to enable the robot to select the best grasp to execute. On the other hand,

grasp synthesis is the problem of finding a suitable set of contacts given an object and some constrains 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 is presented.

2.3.1 Grasp contact models

A contact can be defined as a joint between the finger and the object. Their shape, stiffness and frictional characteristics define the nature of this joint (Mason, 2001). The force applied by a finger at a contact point generates a *wrench* on the object with force and torque components. The contact model maps the wrench at some reference point of the object, usually the centre of mass. Salisbury (1982) proposed a taxonomy of eight contact models. Among these, the more common contact models used in robotic grasping (Fig. 2) are the point contacts with and without friction and the soft-finger contacts (Roa Garzón, 2009). Point contact models, also named rigid-body contact models, assume rigid-body models for the hand and the grasped object while the soft-finger contact models, also called compliant or regularised models, assume that the hand is a deformable element grasping a rigid body (Kao et al., 2008). The former models assume the collision to be an instantaneous and discontinuous phenomenon (discrete event) and the equations of motion are derived by balancing the system's momenta before and after the impact. In contrast, compliant models describe the normal and tangential compliance relations over time.

A *point contact without friction* can only transmit forces along the normal to the object surface at the contact point. No deformations are allowed at the points of contact between the two bodies and, instead, contact forces arise from the constraint of incompressibility and impenetrability between the rigid bodies. These models do not represent the real contact situations that appear in robotic manufacturing operations (Cutkosky, 1989; Lin et al., 2000) and, when used, the machine accuracy is negatively affected. Moreover, they are not capable of predicting the individual contact forces of a multiple-contact fixture (Bicchi, 1994; Harada et al., 2000).

A *point contact with friction* can also transmit forces in the tangential directions to the surface at the contact point. If Coulomb's friction model is used, all the forces that lie within the friction cone with an angle *atan(μ)* can be applied, where μ is the friction coefficient of the contacting materials. Here, contact forces arise from two sources: the rigid-body model assumption for both the hand and the object, and the frictional forces. The use of this contact model in the manipulation planning problem has led to some interesting conclusions. There may be multiple solutions to a particular problem (ambiguity) or there may be no solutions (inconsistency) (Erdmann, 1994).

Finally, the soft contact model is used to model the contact between a soft finger and a rigid object allowing the finger to apply an additional torsional moment with respect to the normal at the contact point (Ciocarlie et al., 2005, 2007; Howe et al., 1988; Howe & Cutkosky, 1996; Kao & Cutkosky, 1992; Kao & Yang, 2004). A typical contact between a soft finger and a contact surface can be modelled by the Hertzian contact model (Hertz, 1882; Johnson, 1985). However, robotic fingertips are made of nonlinear elastic materials. For that reason, the Hertzian contact model does not accurately represent this contact. In Xydas & Kao (1999) and Xydas et al. (2000) a power-law theory is presented for modelling nonlinear elastic contacts present in robotic fingers. It subsumes the Hertzian contact theory. More realistic, and complicated, models have been developed in the last few years that better represent the

contact mechanics for soft fingers (Ciocarlie et al., 2005, 2007; Gonthier, 2007). However, it is the hard finger contacts with friction that are used more often in robotics.
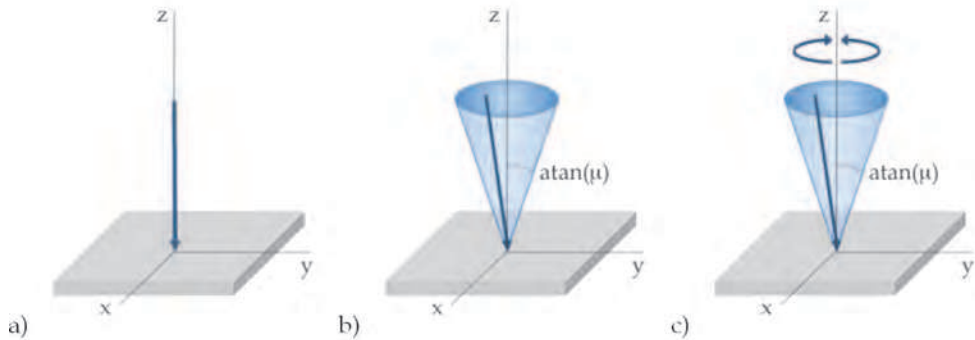

Fig. 2. Contact models commonly used in robotics: a) Point contact without friction; b) Point contact with friction; c) Soft-finger contact

2.3.2 Grasp analysis

After establishing the contact model, the set of contacts defining each grasp can be analysed in order to test its ability to resist disturbances and its dexterity properties. As it is presented afterwards, a grasp can resist disturbances in any direction if it fulfils one of the two closure conditions. However, there is usually more than one grasp that fulfils them. That is why many metrics and approaches have been proposed to evaluate the dexterity of the selected grasps and determine which one is the best to be executed.

Disturbance resistance

The first test for evaluating a grasp consists of determining its ability to constrain the motions of the manipulated object and to apply arbitrary contact forces on the object without violating friction constraints at the contacts (Bicchi, 1995). Two commonly used properties have been proposed to ensure this condition: force and form closure. A grasp is in *force-closure* if the fingers can apply, through the set of contacts, arbitrary wrenches on the object, which means that any motion of the object is resisted by the contact forces (Nguyen, 1988). On the other hand, a grasp is in *form-closure* if the location of the contact points on the object ensures its immobility (Bicchi, 1995).

Form closure is a stronger condition than force closure and it is mostly used when executing power grasps (Siciliano & Khatib, 2008). Force closure is possible with fewer contacts, making it suitable for executing precision grasps, but it requires the ability to control internal forces.

In order to verify the form or force closure property of a grasp, many tests have been proposed (see Liu et al. (2004b) and Roa Garzón (2009) for a review). Most of them define conditions to be satisfied by the grasp wrenches in the wrench space. A *grasp wrench space (GWS)* is the space of wrenches that can be applied to the object at each contact point. The boundary of the wrench space can be calculated as a convex hull. Force-closure then can be determined verifying if the origin of the wrench space lies inside this convex hull (Mishra et al., 1987). Several tests have been proposed to verify this condition, with the one developed

by Ferrari & Canny (1992) being the most widely-used. They proposed to calculate the radius of the largest ball inscribed in the convex hull centred in the origin. Force-closure grasps are the ones where the sphere's radius is larger than zero.

Measures of grasp performance

Many approaches have been proposed to measure the quality of a grasp. Some of the measures focus on evaluating the ability to resist external disturbances, others on evaluating the dexterity. These measures can be classified into two groups depending on whether they consider the location of the contact points on the object or the configuration of the end-effector. There are also some that are a combination of these two approaches (see Roa Garzón (2009) for a thorough review).

Measures from the first group take into account the geometric properties of the objects, their materials and closure properties to evaluate the grasp. For example, Li & Sastry (1998) proposed to calculate the smallest singular value of the grasp matrix, which indicates how far the grasp configuration is from losing the capability of withstanding external wrenches. Others have proposed to favour the grasps whose contact points are distributed in a uniform way on the object surface, which improves their stability (Mirtich & Canny, 1994; Park & Starr, 1992). This can be done by measuring either the angles or the area of the polygon whose vertices are the contact points. The centroid of this polygon is also used to calculate its distance to the object centre of mass (Ding et al., 2001; Ponce et al., 1997). The smaller this distance the better the grasp can resist the effect of external forces. In addition, some other measures take into account the uncertainty in the position of the fingers; therefore instead of contact points they calculate contact regions in which force closure grasps are assured (Nguyen, 1988; Roa Garzón, 2009). The quality of the grasp is measured by the size of these regions.

The previous approaches do not consider any limitation on the finger forces, so that in some cases the fingers have to apply very large forces to resist small perturbations. Other measures do consider limitations on the magnitudes of the finger forces. They can limit the force on each finger or the sum of forces applied by all fingers. Ferrari & Canny (1992) used the largest ball not only to evaluate grasp closure but also to measure the grasp quality. This is a geometric representation of the smallest perturbation wrench that breaks the grasp, independently of its direction. It has been widely used by the robotics community (Borst et al., 2003; Miller & Allen, 1999; Roa Garzón, 2009). The volume of the ball is also considered as a quality measure with the advantage that it remains constant independently of the used torque reference system (Miller & Allen, 1999).

When a task is specified to be performed after the object is grasped, the quality of the grasp can be measured with its ability to counteract the expected disturbances during the task execution. The set of all wrenches that are expected to be applied on the object defines the *task wrench space (TWS)* and can be approximated as an ellipsoid (Li & Sastry, 1988) or as a convex polytope (Haschke et al., 2005; Zhu at al., 2001). The problem with these approaches is that modelling the TWS can be quite complicated (Borst et al., 2004). Pollard (2004) introduced the concept of an *object wrench space (OWS)*, which is the set of wrenches generated by applying a distribution of disturbance forces on the surface of the object. Borst et al. (2004) proposed the use of the largest factor by which the OWS can fit the GWS as the measure of the grasp quality.

On the other hand, there are measures that consider the configuration of the end-effector, requiring the hand-object Jacobian for their calculation (Roa Garzón, 2009). An example of

this group is a measure that favours a grasp that, given certain velocities in the finger joints, produces the largest velocities on the grasped object, calculated with the volume of the manipulability ellipsoid (Yoshikawa, 1985). There is another measure that penalises the joints of the hand being in their maximum limits, calculating the deviation of the joint angles from their centres (Liegeois, 1977). Additionally, there are other measures in this group that also consider the task, giving higher quality indexes to the grasps which ensure the maximum transformation ratio along the direction wrenches more likely to be applied on the object when executing it (Chiu, 1988).

2.3.3 Grasp synthesis

Given an object, grasp synthesis algorithms should provide a suitable set of contacts on the object surface and determine an appropriate hand configuration. Usually they take the geometry of the object as an input to select optimal force-closure contact locations. These contacts are the starting point for grasp analysis and dexterous manipulation methods.

Some approaches give only information about the finger contact locations on the object without considering the hand constraints. They can result in stable grasps that are not reachable in practice by the robot hand. Moreover, even if they are reachable, it is difficult to position the fingers precisely on the contact points because there will be always unavoidable errors locating the end-effector (Morales et al., 2006).

Alternative approaches, called knowledge-based approaches, have considered the configuration of the hand by generating the grasp with a predefined set of hand postures. The idea of hand preshapes started with studies of the human prehension capabilities (Napier, 1956) that introduced the distinction between power and precision grasps. Following this work, Cutkosky (1989) created a taxonomy in which details of the task and the object geometry are taken into account. Since then, several papers have adopted this approach for grasping (Morales et al., 2006; Stansfield, 1991; Wren, 1995). Miller et al. (2003) used a simulator called GraspIt! to test the set of hand preshapes on a 3D model of the object. Using a simulator has many advantages, including the ability to plan grasps in complex environments involving obstacles and also to check the reachability constraints of the robot arm. More recently OpenRAVE, a planning architecture that has a more flexible design, has been proposed to automate this process (Diankov, 2010).

Despite many years of research and all the advances we have reviewed, the robotics community is still not able to build a manipulator with similar capabilities to the human hand. The robot hands constructed until now are only simplifications (Fig. 3), given the complexities not only at the sensor and actuator level, but also at the control level. They vary from the easiest to control, such as 2-jaw grippers, to more anthropomorphic hands like the Salisbury Hand, the Utah-MIT Hand, the Barrett Hand, the ARMAR III Hand or the DLR Hand II (see Biagiotti et al. (2002) and Parada et al. (2008) for a review).

3. Hand biomechanical model proposal

In this section, the current knowledge on biomechanical, ergonomics and robotics hand models is used to draw out the rules for developing a realistic and self-contained biomechanical model of the hand.

Based on the literature review, current hand biomechanical models allow estimating the muscular patterns required to perform a movement while counteracting a system of external forces. But their use for studying object grasping is limited. On the one hand, biomechanical
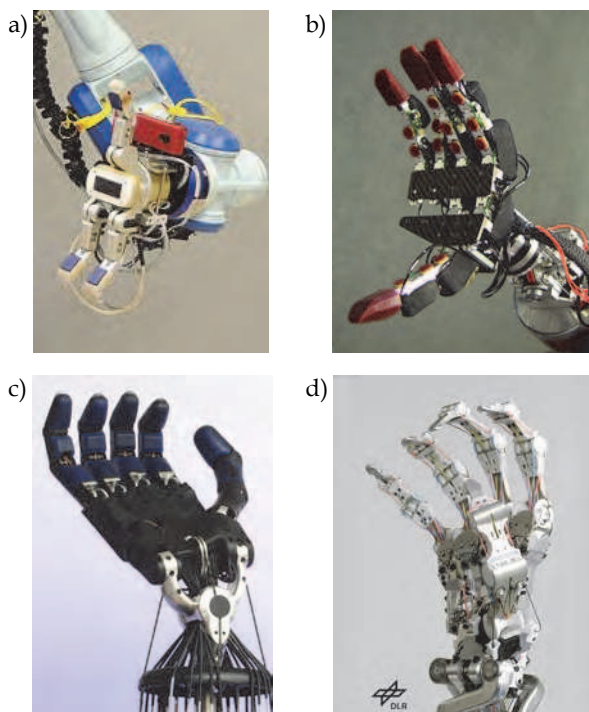
Fig. 3. Anthropomorphic robot hands: a) Barrett Hand (courtesy of the UJI Robotics Intelligent Lab); b) ARMAR III Hand (courtesy of the Institute for Anthropomatics at KIT); c) Shadow Hand C5 (courtesy of Shadow Robot Company); d) Anthropomorphic DLR Hand Arm System (courtesy of DLR Robotics and Mechatronics Center)

models lack realism for assessing the use of handheld products from an ergonomics point of view. Hand models in ergonomics have reached a high level of realism but do not allow for mechanical analyses. On the other hand, biomechanical models are not self-contained, as they need contact information to be input to the model. Current models do not allow predicting grasping postures nor evaluating contact forces and zones, much less predicting the movements while grasp planning. Quality grasp measures in robotics allow comparing different robotic grasping postures and could be adapted to human grasping.

A detailed proposal for modelling the different components of the hand is provided below: joints-kinematics, muscles, ligaments and passive tissues, skin, contact with objects and neuromuscular control. The features that we require in order to create a model are:

- The model has to simulate the complete hand in order to allow the study of any grasp.
- The model has to be scalable to allow the simulation of different population groups.
- The model has to simulate and show the grasping of an object in a realistic way.
- The model has to estimate the muscular patterns required to perform a movement while counteracting the system of external forces that define the object manipulation. Furthermore, the model has to estimate the articular forces at the hand joints.
- The model has to be dynamic in order to allow the study of any grasping task (slow or fast) during the object manipulation.

- The model has to predict feasible grasping postures for a given object and provide the contact information required for evaluating the grasp
- The model has to incorporate quality grasping measures for evaluating the grasp.

The model proposed in this section has been developed in a scalable way, choosing two very well known anthropometric parameters of the hand that are easy to measure and representative of the hand size. The parameters are the hand length (HL) and hand breadth (HB) and are shown in Fig. 4.
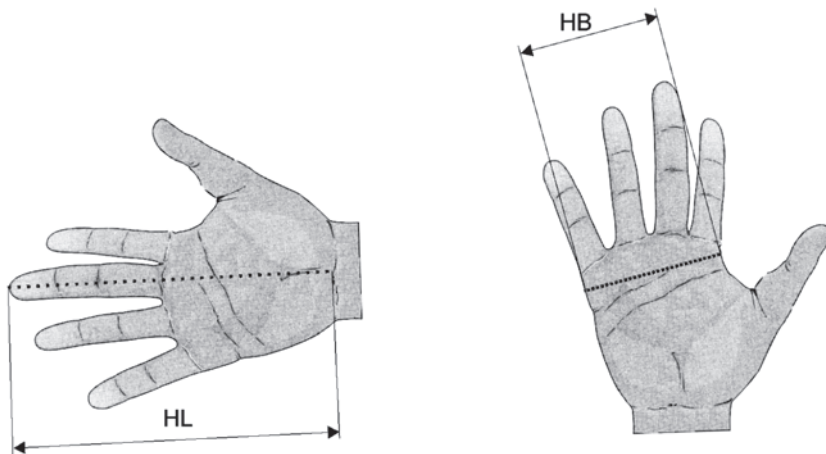

Fig. 4. Parameters used to scale the model: HL (hand length) and HB (hand breadth)

3.1 Kinematics

In order to achieve realistic grasping postures, care has to be taken when selecting the appropriate DOF among the different hand bones. The DOF have to allow the hand model to reach the hand posture for any grasping task. In this sense, it is important that the model considers not only the thumb and finger movements but also the palm arching.

The hand has been considered as five skeletal open chains of rigid bodies connected to the carpus through different joints which characterise the kinematic behaviour of the chains.

Distal and proximal interphalangeal (DIP and PIP) joints of the fingers as well as the interphalangeal (IP) joint of the thumb are trochlear joints, capable only of flexion/extension movements (Brand & Hollister, 1992). These joints are modelled as one DOF joints by means of defining a rotation axis connecting the adjacent phalanxes (hinge joint).

Thumb and fingers metacarpophalangeal (MCP) joints are condylar joints, capable of flexion/extension and abduction/adduction movements (Brand & Hollister, 1992). The thumb carpometacarpal (CMC) joint is a saddle joint, capable also of flexion/extension and abduction/adduction movements (Brand & Hollister, 1992). All these joints are modelled as two DOF joints by defining two axes of rotation connecting the adjacent segments. The axes are neither intersecting nor orthogonal (Brand & Hollister, 1992), so that a virtual link is used to connect both axes (Giurintano et al., 1995).

Finally, the hand model allows the arching of the palm by modelling the CMC joints of the little and ring fingers. These joints are arthrodial joints, with a very limited range of movement (Kapandji, 1998). They have been modelled as one DOF joints by means of

defining a flexion/extension axis of rotation connecting the carpus to each metacarpal. The orientation of the axes is defined oblique in order to appropriately simulate the arching of the palm (Kapandji, 1998). Due to the important role that the shape of the palm plays in grasping, this model is considered more suitable for grasping simulation than others in the literature.

The data for the location and orientation of the rotation axes comes from An et al. (1979), Buchholz et al. (1992) and Hollister et al. (1995). Axes data and link lengths are fully scaled with respect to the hand length and hand breadth (Sancho-Bru, 2000). Limits for the joints have been obtained from Tubiana (1981) and Tubiana et al. (1996).

In order to study the forward and inverse kinematics of the hand, the Denavit- Hartenberg method from the robotics field (Denavit and Hartenberg, 1955) was adapted to define the position of any segment point.

3.2 Musculo-tendon action

Muscles and tendons control the movement of the skeletal chains. Muscles have been considered using a simple Hill three-component model (Hill, 1938) that takes into account the muscle activation level (α) and the force-length and force-velocity relationships, as well as the different index of architecture of muscles. The model considers a contractile element (CE), which is the basic component that generates force, a parallel elastic element (PEE), which is responsible for the passive force generated by the muscle when it is stretched, and a series elastic element (SEE), the muscle tendon unit, which has been considered to be inextensible (Fig. 5).
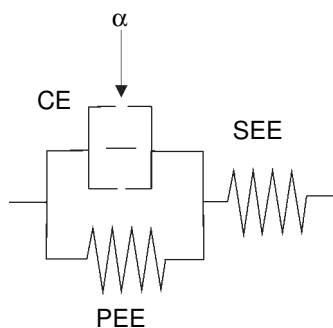

Fig. 5. Hill's three-component model for the muscles

The force a muscle can exert depends on the actual muscle length and contraction velocity. It is widely accepted (An et al., 1991) that the maximum force a muscle can exert in optimal conditions is proportional to its physiological cross-sectional area (PCSA):

$$F_{\max} = PCSA \cdot S_{\max} , \qquad (1)$$

where S_{max} is the maximum stress the muscle can bear, which has been considered the same for each muscle (An et al., 1991).

The strain of tendons is insignificant for the magnitude of forces developed by the muscles (Goldstein et al., 1987). Under this consideration, the SEE has been considered to inextensible, so that the force the muscle exerts (F) can be written as:

$$F = F_{max}(F_{CE} + F_{PEE}) \,, \tag{2}$$

where F_{CE} and F_{PEE} are the normalised forces delivered by the CE and PEE, respectively.
The force exerted by the muscle can be decomposed into an active force and a passive force corresponding to the forces delivered by the CE and PEE, respectively. The force delivered by the CE is related to the muscle architecture and is a function of the muscle length l_{CE}, the contraction velocity v_{CE}, and the muscle activation level α (from 0 to 1), which is controlled by the central nervous system (Kaufman et al., 1991):

$$F_{CE} = \alpha \cdot F_l(l_{CE}) \cdot F_v(v_{CE}) \tag{3}$$

where F_l and F_v are the non-dimensional force-length and force-velocity relationships.
A characteristic bell-shaped curve exists between force and length of the muscle. To model this dependence, the expression proposed by Kaufman et al. (1991) has been used:

$$F_l(\varepsilon, i_a) = e^{-\left[\frac{(\varepsilon+1)^{0.96343\left(1-\frac{1}{i_a}\right)}-1.0}{0.35327\cdot(1-i_a)}\right]^2} \quad \text{for } i_a < 1 \tag{4.a}$$

$$F_l(\varepsilon, i_a) = e^{-[2.727277\cdot\ln(\varepsilon+1)]^2} \quad \text{for } i_a = 1 \tag{4.b}$$

where i_a is the muscle architecture index, defined as the ratio between the muscle fibre length and the muscle belly length, and ε is the muscle strain due to its lengthening from l_o, the muscle length for the optimal conditions.
The force a muscle can exert decreases when the contraction velocity of the muscle fibres increases. To model this dependence the expression proposed by Hatze (1981) has been used

$$F_v(\dot{\eta}) = \frac{0.1433}{0.1074 + e^{-1.409\cdot\sinh(3.2\cdot\dot{\eta}+1.6)}} \tag{6}$$

where $\dot{\eta}$ is the normalised contractile element velocity, given by the ratio between the lengthening velocity of the muscle ($\dot{\varepsilon}$), and its maximal value ($\dot{\varepsilon}_{max}$).
The force generated by the PEE is a function only of its length. An exponential relationship has been considered in this case (Lee & Rim, 1990; Kaufman et al., 1991), with b_1 and b_2 muscle dependent constants:

$$F_{PEE} = b_1 \cdot e^{b_2 \cdot \varepsilon} - b_1 \,, \tag{7}$$

The scalability of the muscular action is achieved by scaling the PCSA of the muscles with respect to the product of hand length and hand breadth parameters (Sancho-Bru et al., 2008) from its value for $HL = 18.22$ cm and $HB = 8.00$ cm.

$$\frac{PCSA(HL, HB)}{PCSA(\overline{HL}, \overline{HB})} = 1 + 0.01333 \cdot (HB \cdot HL - \overline{HB} \cdot \overline{HL}) \tag{8}$$

The muscles considered on each skeletal chain are listed in Table 1. PCSA data for index finger muscles have been taken from Valero-Cuevas et al. (1998); data for the remaining muscles have been obtained from Brand & Hollister (1992). Muscle stress limit (S_{max}) has been obtained from Zajac (1989). Fibre and muscle lengths and the constants b_1, b_2 for index

finger muscles have been taken from Lee & Rim (1990); data for the remaining extrinsic muscles have been obtained from Lemay & Crago (1996) and for the remaining intrinsic muscles from Jacobson et al. (1992). The muscle maximal lengthening velocity ($\dot{\varepsilon}_{max}$) has been taken to be 2.5 s^{-1} (Kaufman et al., 1991).

Index	Medial	Ring	Little	Thumb
1st FP	2nd FP	3rd FP	4th FP	APB
1st FS	2nd FS	3rd FS	4th FS	FPB
1st EDC+EI	2nd EDC	3rd EDC	EDQ	OPP
1st LU	2nd LU	3rd LU	4th LU	ADD
1st DI	2nd DI	4th DI	3rd VI	1st DI
1st VI	3rd DI	2nd VI	FDQ	APL
			ADQ	EPB
				FPL
				EPL

Table 1. Muscles modelled on each skeletal chain (acronyms in the nomenclature section)

Most of the muscles do not act directly on the bones, but transmit the force to the tendons, which finally insert into the bones. To model the tendon action crossing the joints, straight lines connecting 2 points have been considered, one fixed with respect to the proximal bone and the other one with respect to the distal bone (Fig. 6a). This approximation has been found to be close enough to the behaviour of all tendons with the exception of extensors (An et al., 1979), for which Landsmeer's model I has been considered (Fig. 6b). The data for the points defining the tendon actions have been obtained from An et al. (1979).
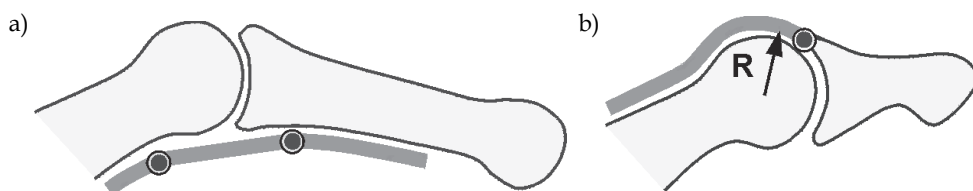

Fig. 6. Models for the tendons crossing the joints: a) Straight lines; b) Landsmeer's model I

The extensor hood mechanisms of the fingers are modelled as a tendon net. The net allows for the connection and division of the tendon paths. The insertions and connection points considered for the tendon nets on each skeletal chain are shown in Fig. 7. Appropriate force balances have been considered in the connecting points of this deformable tendon net. Second DI, fourth DI and ADQ tendons do present a double insertion into the proximal phalanxes and into the extensor aponeuroses. A force distribution proportional to the amount of fibres of each branch (Eyler & Markee, 1954) has been considered.

The muscle force-length and force-velocity relationships presented above require the calculation of the lengthening of the muscles from l_o as a function of time. Having considered the tendons inextensible, the muscle lengthening coincides with the tendon excursion. To calculate the length of the tendon path crossing each joint (l_i), straight lines connecting the points have been considered, except for the extensor tendons, for which a circular path has been considered.
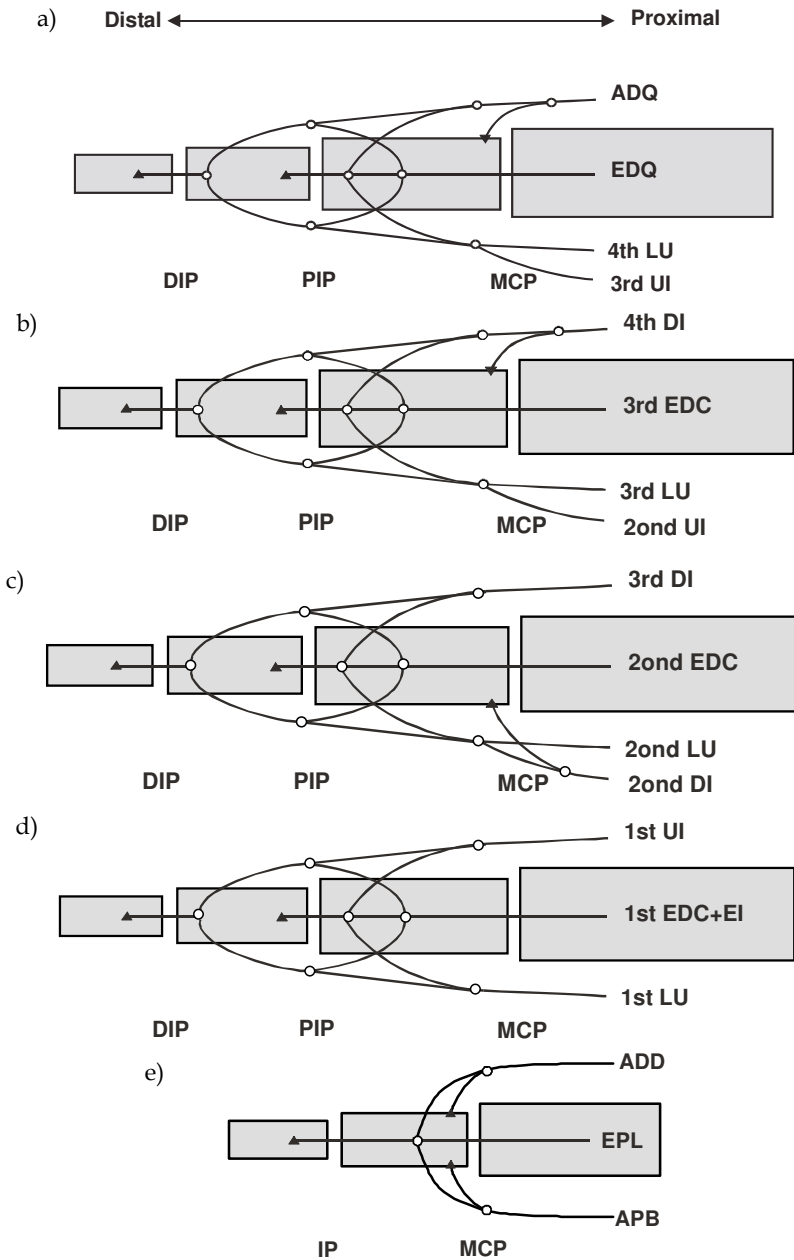
Fig. 7. Sketch of the extensor mechanisms of the fingers and thumb (dorsal view) showing the insertions into the bones (▲) and the connections and splittings considered (○): a) little finger; b) ring finger; c) medial finger; d) index finger; e) thumb.

The data for the location of the points defining the tendon paths comes from An et al. (1979) and Buchholz et al. (1992), and are also scaled with respect to the hand length and hand breadth (Sancho-Bru, 2000).

3.3 Ligaments

In previous work, we showed the importance of modelling the effect of ligaments for studying free finger movements. In the case of grasping, their consideration is not so relevant. Their effect can be neglected for studying power grasps, but they can play an important role in the case of some precision grasps, particularly those involving fast movements.

In the case of DIP and PIP joints of fingers and thumb, the insertion of the collateral ligaments on the proximal segment of the joint corresponds to the flexion-extension axis (Dubousset, 1981). Therefore, they do not develop any flexion-extension moment over the joint and they do not need to be modelled. In the case of MCP joints, the proximal insertion of the lateral ligament on the metacarpal head remains dorsal to the center of the articular curvature (Fig. 8), so that collateral ligaments are lax in extension, but they become taut in flexion, decreasing significantly the range of lateral movement (Craig, 1992; Dubousset, 1981; Kapandji, 1998). Tension on the radial and ulnar ligaments increases with adduction and abduction of the MCP joint, respectively. Furthermore, the line of action of the ligaments remains dorsal to the flexion- extension axis of the joint (Craig, 1992), developing an extension moment over the joint, in addition to the abduction-adduction moment.
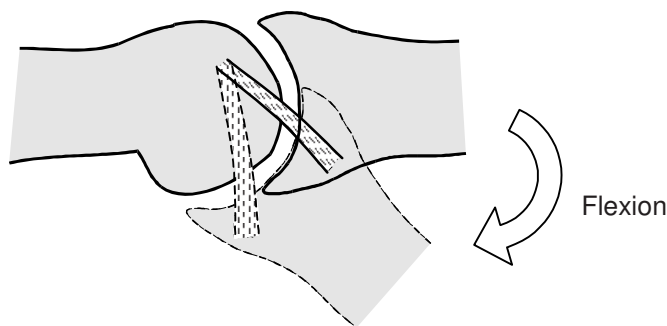

Fig. 8. Collateral ligament over MCP joints becomes taut with flexion.

Both ulnar and radial ligaments over MCP joints have been considered. A unique fibre for each ligament has been considered, joining two points representing the insertions into the bones. One point is fixed with respect to the metacarpal, and the other one with respect to the proximal phalanx. No interaction between bone and ligament has been considered; therefore the ligament path is a straight line between the insertion points. Its non-linear behaviour has been taken into account considering a quadratic relationship between the force developed by the ligament (F_{lig}) and its elongation (Mommersteeg et al., 1996)

$$F_{lig} = K \cdot \left(L_{lig} - L_{lig,o} \right)^2 , \tag{10}$$

where K is the characteristic constant of the ligament, L_{lig} the length of the fibre representing the ligament, and $L_{lig,o}$ the unstrained length of the ligament.

The data for the ligament insertion points have been obtained from the geometric model presented in Youm et al. (1978), and the stiffness constant has been estimated to be 750 N/cm^2 from Minami et al. (1985).

3.4 Skin and contact with objects

One of the applications of the biomechanical model is its use in assessing the use of handheld products from an ergonomics point of view. To accomplish that goal, the model has to incorporate a realistic model of the skin from the visual point of view. The advances in computer animation have made possible the development of a number of convincing surface skin models.

We propose to use a surface skin model similar to that of Endo et al. (2007) or Goussous (2007). The surface skin model is a 3-dimensional polygonal mesh for the hand surface generated from CT images. The geometry of the skin model is defined at only one opened posture. A surface skin deformation algorithm defines the deformed geometry of the surface skin model when the posture of the kinematic model is changed (Fig. 9). The algorithm assigns each bone a capsule-shaped *envelope*. Vertices of the modified skin within these envelopes move with the bones. Where envelopes overlap, vertex motion is a blend between the envelopes. The influence of each bone for vertices within the intersection of two bones' envelopes is controlled by assigning weight values. The ratio of a vertex's weight values, which always total 1.0, determine the relative extent to which each bone's motion affects the vertex. Furthermore, the model gets scaled when the kinematic model is scaled.

As stated before, the model has to simulate and show the grasping of an object in a realistic way. To satisfy this requirement, it is not enough to have a visually realistic model of the surface skin. The model must also be able to predict feasible grasping postures.

Fig. 9. Surface skin model

In order to generate grasp postures automatically, we propose to use a grasping algorithm based on that of Choi (2008). This algorithm uses a function to automatically generate a natural grasping motion path of the hand model from a fully opened state to a clenched one. The goal is to find contacts between the surface hand skin and the object surface while rotating the joint angles of the fingers. Care has to be taken to properly choose the rotation rate of the finger joints, as it affects the final posture prediction. Based on the results from Choi (2008), we propose to use a variable rotation algorithm, by describing rotations of all

joints at observation-based rates. To select the appropriate rotation rate we propose the use of neural networks, similar to those used in Kyota et al. (2005) and Rezzoug & Gorce (2008). This will require intensive experimental work beforehand to record the postures for grasping objects (of different shapes, sizes, weights, etc.) when performing different tasks (power and precision). The experimental data have to be analysed in order to characterise the human grasp and find the parameters affecting the grasping posture. These parameters will be used as input to the neural network to estimate a tentative clenched posture. The rotation rate is defined by the difference between the angles of the fully opened state and the tentative clenched one.

In order to generate the grasp, a contact model is required. We need to check whether the surface skin model makes contact with the surface of the object model. In reality, the surface of a hand is deformed when making contact with the object. Generally, this deformation has a non-linearly elastic property, and it could be simulated using finite element analyses. But this would need a long execution time. This is unacceptable for our model where a large number of different grasp postures have to be generated and tested within a practical time.

Therefore, we propose to consider a simple geometric collision-detection algorithm based on the one used by Endo et al. (2007). The algorithm allows the penetration of the surface skin model and the object model. This penetration is limited by a tolerance that relates to the hand stiffness of each contact region.

The distances between the points on the skin surface and the object are calculated while the joint angles of each joint rotate according to the specific joint rotation algorithm. When the maximum penetration distance between the skin surface points and the object reaches the given tolerance, the contact is achieved and the joint rotation ends. When distal segments of all four fingers make contact with the object, the simulation terminates.

As we have mentioned previously, the model has to provide the contact information required for evaluating the grasp. If a classical robotics quality measure of the grasp is to be performed, the only data needed are the contact points and associated normal vectors at these points, which are easily obtained from the proposed contact model.

When trying to estimate the muscular pattern associated with a grasp, the model needs more contact information. The contact forces between the object and the hand have to be considered in this case. Unlike what happens with robots, real human fingers conform to the grasped object shape. As the contact finger surface is deformable the contact does not occur at just one point but over some finite area that increases as the normal forces increase. Due to this effect, in addition to the normal force and tangential force due to friction, human finger contact may support frictional torsional moments with respect to the normal at the contact point. This clearly shows that the consideration of rigid contact commonly used in robotics is not appropriate for use in studying the human grasp, and a soft contact has to be modelled. Most objects manipulated by human hands are much stiffer than human hands, and it is reasonable to consider the objects to be grasped as rigid bodies, and the hand as a deformable body.

Different soft contact models have been investigated and proposed in order to better account for this deformation effect in the context of soft finger contacts (Ciocarlie et al., 2005, 2007; Gonthier, 2007). In Ciocarlie et al. (2007) friction constraints are derived based on general expressions for non-planar contacts of elastic bodies, taking into account the local geometry and structure of the objects in contact. The following approximation can be used to express the constraint relating the magnitudes of frictional force (f_t) and moment (τ_n):

$$f_t^2 + \frac{\tau_n^2}{e_n^2} \leq \mu^2 \cdot P^2 \ , \tag{11}$$

where P is the total load applied in the direction of the contact normal, μ is the friction coefficient and e_n is called the eccentricity parameter (height of the ellipsoid described by Eq. 11). Considering a Winkler elastic foundation (Johnson, 1985) of depth h and elastic modulus K, the eccentricity parameter is given by:

$$e_n = \frac{8}{15} \cdot \sqrt{a \cdot b} \ , \tag{12}$$

where a and b can be calculated from the relative radii of curvature R' and R'' of the objects in contact and the compression δ of the elastic layer:

$$a = \sqrt{2 \cdot \delta \cdot R'}; \ b = \sqrt{2 \cdot \delta \cdot R''}; \ \delta = \sqrt{\frac{P \cdot h}{K \cdot \pi \cdot (R' \cdot R'')^{1/2}}} \ , \tag{13}$$

The actual grasping forces for a given posture will be obtained by considering that they have to satisfy the dynamic equilibrium of the grasped object. There is not a unique set of forces that ensures the equilibrium but we have to take into account the biomechanical limitations (maximal muscle forces) and the control performed by the central nervous system. In an effort to minimise the computational cost, we propose to uncouple the computation of the contact forces from the neuromuscular control model. This can be done by considering that the central nervous system is trying to attempt performing the grasp with minimal contact forces, as implemented for robots in the work of Liu et al. (2004a).

3.5 Neuromuscular control

The movement of the skeletal chains, together with the contact forces and the corresponding application points are input to the model. The problem to be solved is the derivation of the muscle activation levels required to produce the given motion under the external loads. It is, therefore, an inverse dynamics problem.

The dynamics equations of the open chain of rigid bodies have been derived using the Lagrange method (García de Jalón & Bayo, 1994). For a system with m generalised co-ordinates q_k, this equation is expressed as:

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{q}_k} - \frac{\partial L}{\partial q_k} = Q_k^{nc} \quad k = 1, \ldots, m \ , \tag{14}$$

where L is the Lagrangian function and Q_k^{nc} are the generalised non-conservative forces. The generalised coordinates have been considered coincident with the system DOF ($m=23$).

Eqs. 14 together with the force balances of the tendon nets lead to an indeterminate problem. For example, in the case of the index finger, there are 12 equations (four corresponding to the DOF considered and eight to force balances in the tendon net) and 18 unknowns (six muscle forces and 12 branch forces of the tendon net). There is not a unique combination of muscular efforts that satisfy the dynamic equilibrium constraints. To solve the problem, a criterion chosen by the central nervous system to determine the muscle action control must be introduced. Our proposal is to maximise the endurance. According to Crowninshield and Brand (1981), this is achieved by minimising the non-linear objective function

$$OBJ = \sum \left(\frac{F_i}{PCSA_i} \right)^n , \tag{15}$$

with n between 2.0 and 4.0, and where F_i represents the force exerted by muscle i, and $PCSA_i$ its physiological cross-sectional area. In this case, $n = 2$ will be used. This function is minimised when subjected to Eq. 13 together with the force balances of the tendon nets. Additional constraints are that tendon forces must be non-negative, and the limits of muscle forces obtained from Eqs. 2 and 3 varying the muscle activation level from 0 to 1

$$F_{PEE} \cdot F_{max} \le F \le (F_l \cdot F_v + F_{PEE}) \cdot F_{max} . \tag{16}$$

3.6 Grasp evaluation

A global grasp evaluation can be performed through the use of the proposed model, merging the knowledge from ergonomics, robotics and biomechanics. The classical ergonomics evaluation of grasp posture and reachability is possible, for different percentiles of the population represented by the corresponding anthropometric parameters. Furthermore, CHTD evaluation can be performed by using the predicted postures and muscle forces.

It is advisable to use force closure from robotics as a part of the proposed model; once a grasping posture is estimated by the grasping algorithm, force closure should be assured before consuming time in determining the contact forces. Any of the robotics quality measures could be used for evaluating the grasp. Depending on the task to be performed, it would be better to use a grasp quality measure to evaluate the disturbance resistance or a grasp quality measure to evaluate the manipulability.

But the most relevant contribution to grasp evaluation has to come from biomechanics analysis. Grasp measures related to the muscle and articular forces have to be investigated. Just to provide insight into this sense, and to ensure coherence with our model formulation, we propose the use of Eq. 15 as a quality measure related to fatigue that we can call *fatigue index*: the smaller the fatigue index the better will be the grasp. For power grasps, an alternative measure can be the difference between the maximal force the hand can exert on the grasped object for the posture being analysed and the real contact forces estimated by the contact model; this alternative measure can be seen as a safety margin for the muscle forces, that we can call *muscle safety margin index*. Additional measures can be investigated, such as the maximal contact pressure, etc.

4. Conclusion

A realistic and self-contained biomechanical model of the hand has been proposed by merging the current knowledge of biomechanics, ergonomics and robotics. The model simulates the complete hand and can easily be scaled to study different percentiles of populations. It has a realistic representation that allows the ergonomic evaluation of products. The model is dynamic and can be used to study the muscular patterns associated with a specific grasp. It allows predicting feasible grasping postures and provides the contact information required for evaluating the grasp. Finally, the model incorporates original quality grasping measures such as the fatigue index and the muscle safety margin index, in addition to the usual robotics and ergonomics metrics and evaluations. All the

abovementioned features are performed in a virtual environment, without external experimental data.

5. Acknowledgment

6. Nomenclature

3D	Three-dimensional	FP	Flexor profundus
ADD	Adductor pollicis	FPB	Flexor pollicis brevis
ADQ	Abductor digiti quinti	FPL	Flexor pollicis longus
APB	Abductor pollicis brevis	FS	Flexor superficialis
APL	Abductor pollicis longus	GWS	Grasp wrench space
CE	Contractile element	HB	Hand breadth
CHT	Cumulative hand trauma		
D	disorders	HL	Hand length
CMC	Carpometacarpal	IP	Interphalangeal
DI	Dorsal interosseous	LU	Lumbrical
DIP	Distal interphalangeal	MCP	Metacarpophalangeal
DOF	Degrees of freedom	OPP	Opponens pollicis
EDC	Extensor digitorum communis	OWS	Object wrench space
		PCS	Physiological cross-sectional
EDQ	Extensor digiti quinti	A	area
EFM	Elastic foundation model	PEE	Parallel elastic element
EI	Extensor indicis	PIP	Proximal interphalangeal
EPB	Extensor pollicis brevis	SEE	Series elastic element
EPL	Extensor pollicis longus	TWS	Task wrench space
FDQ	Flexor digiti quinti	VI	Volar interosseous

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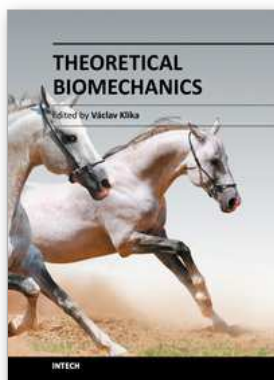
Theoretical Biomechanics

Edited by Dr Vaclav Klika

During last couple of years there has been an increasing recognition that problems arising in biology or related to medicine really need a multidisciplinary approach. For this reason some special branches of both applied theoretical physics and mathematics have recently emerged such as biomechanics, mechanobiology, mathematical biology, biothermodynamics. This first section of the book, General notes on biomechanics and mechanobiology, comprises from theoretical contributions to Biomechanics often providing hypothesis or rationale for a given phenomenon that experiment or clinical study cannot provide. It deals with mechanical properties of living cells and tissues, mechanobiology of fracture healing or evolution of locomotor trends in extinct terrestrial giants. The second section, Biomechanical modelling, is devoted to the rapidly growing field of biomechanical models and modelling approaches to improve our understanding about processes in human body. The last section called Locomotion and joint biomechanics is a collection of works on description and analysis of human locomotion, joint stability and acting forces.

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