



## ROBOT ERGONOMICS: TOWARDS HUMAN-CENTRED AND ROBOT-INCLUSIVE DESIGN

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### Abstract

This paper presents a cross-disciplinary approach to the design of robots and the designed environments they will inhabit and the objects they will operate in applications of social and service robotics. Such an approach brings together roboticists, architects, product, and interior designers in realizing new ways of collaboration to design innovative spaces and products that are ergonomically designed for diverse users as well as for robots. A design paradigm is proposed for realizing successful robot-inclusive designs using a case study of door handles to test our robot ergonomic principles.

*Keywords: technology development, architectural design, ergonomics, robotics*

### 1. Introduction

Ergonomics is the scientific study of “interactions among humans and other elements of a system, and the application of theory, principles, data and methods to optimize human well-being and overall system performance” (IEA, 2017). Its etymology refers to the study of work (*ergon*, work and *nomos*, laws). As robots gain increasing levels of agency, we suggest that autonomous social robots can be considered a new user category and suggest a “robot factors” link between the design of robots and the design of everyday spaces and products. “Robot Ergonomics” is thus defined here as the study of robot activity for overall system performance in order to build awareness of the capabilities of robots in the design decisions across disciplines (Mohan et al., 2015). By integrating robots as a special population, the goal is to develop a human-centred and robot-inclusive design approach where simplicity and cost-effectiveness are considered to support robot activity. This work brings a designerly lens to the field of social robotics broadly defined the study and development of new applications of autonomous machines designed for social interaction with humans in everyday situations. This work aims to extend work on “Robot Inclusive Spaces” which adopts interdisciplinary design strategies to overcome the research challenges in the real-world deployment of social robots (Mohan et al., 2015). Integrating human and robot factors is expected to lead to design trade-offs, hence the following fundamental laws for robot-inclusiveness are formulated to orient this work – paraphrasing Isaac Asimov’s renowned laws:

- First Law of Design for Robots: “An environment or a product designed for robot users is first and foremost a Human-Centred design and shall never present an inconvenience, threat, obstacle, annoyance, or damage to human users”
- Second Law of Design for Robots: “An environment or product must be fit for social robots and support their activity, guaranteeing accessibility, functionality, protection, and intuitive interactions with human users, except where such support would conflict with the First Law”

- Third Law of Design for Robots: “An environment or product designed for robot users must seek to minimize computational demands, complexity, and costs, except where such criteria would conflict with the First or Second Law”

This work is grounded on embodied social cognition, which focuses on the interplay between the environment, the brain and the body (Lindblom, 2015). Viewing social robots as situated agents, our work seeks to connect design decisions across the entire system. This work defies the current way in which roboticists aim to build increasingly able robots, while product designers and architects design the everyday spaces where these robots will act without considering robots as future users (Mohan et al., 2015). The paper continues with a review of the background literature on ergonomics in design, the current state in social robotics and the divide that this work aims to bridge between design decisions in robotics and more traditional design fields. Section 3 provides design principles for robot ergonomics suggesting three design approaches. Section 4 presents a case study to test this approach based on the criteria and rules of a leading robot competition. Section 5 closes with a discussion on implications, open challenges and future extensions of this work.

## 2. Background

Ergonomics in product design and architecture gained importance in the second half of the twentieth century. Today it can be viewed as the study of human activity to design more friendly products and spaces. To conceive more ergonomic products and spaces, designers select and apply guidelines and heuristics according to the problem conditions including their target users. Measurements selected for each parameter of a design can correspond to average metrics, or more frequently to the top or bottom percentile of the population in order to accommodate a majority of users (Neufert et al., 2012).

A key goal of ergonomics is that it is not prescriptive, it supports evidence-based decision making in design by offering tables of measurements, optimal parameters, and rules of thumb that designers must creatively interpret and apply in their design process. This freedom also entails that ergonomic flaws are a common cause of ‘bad design’ causing considerable challenges to understand and use everyday designs (Norman, 2013). By proposing “Robot Ergonomics”, we pursue the systematic formulation of design methods, techniques and tools that guide designers of robots, designers of products and designers of spaces, but do not constraint their creative freedom to produce innovative solutions.

Social or service robots for personal and domestic applications have grown over the last decade with the commercial success of floor cleaning robots, robot mowers and edutainment platforms. Such robots must safely work beside and cooperate with people in changing indoor and/or outdoor environments. Cases of commercial success stories include: Paro, iRobot Roomba, Pepper and Nao, Kiva, and the Toyota HSR (RoboCup, 2016). Despite the advances in artificial intelligence, mechanics, sensing, actuation, and control in the past two decades, social and service robots are still far from working autonomously in fully dynamic social environments. Interacting with everyday products in dynamic settings shared with humans offers serious research challenges (RoboCup, 2016). One particularly hard problem is skilful manipulation, i.e., the desirable feature for a domestic robot to grasp a wide range of objects including those that tend to be similar but not equal to each other, as well as objects that are unknown beforehand but that can be grasped or handled (RoboCup, 2016).

Skilful manipulation is essential for social and service robots to work in human environments. However, to date, robots can only perform complex manipulations in simulation and in controlled environments, or when a human tele-operates them. The manipulation of objects (to grab a glass, screw the lid of a jar, or open a door) even for the most advanced robots requires complex control systems, artificial vision, sensors, actuators and machine learning programming that demand considerable computing, material, financial and development resources.

Human environments can be very challenging for robot manipulation, especially since everyday environments and objects are designed to be well-matched to fully-able human bodies and capabilities (Kemp et al., 2007). Social robots may use a variety of end effectors to operate in the environment, including: mechanical, vacuum, magnetic, adaptive, and adhesive (Martell and Gini, 2007). Seemingly simple tasks such as door handling can be unexpectedly challenging for service robotics since they require a series of complex perception, processing, and action skills. Perception alone involves

identifying an object's location, orientation, size, and type upon which the robot would arrive at a series of appropriate control actions. Many approaches have been proposed (Klingbeil et al., 2010), but solutions are often highly constrained and expensive and follow a design strategy that focuses only on the design of the robots disconnected from the design of the world they interact with.

The current gap between robot design and spatial or built environment design is clear in the major international competitions in both fields. In RoboCup@Home (RoboCup, 2016) the ultimate target scenarios are “domestic areas of daily life”, and a set of benchmark tests in non-standard scenarios are developed to assess robot capabilities including navigation in dynamic environments and adaptive object manipulation. For this purpose, spaces, furniture and everyday objects are selected by the organising committee, some of which are disclosed to the participants prior to the competition, and others remain unknown to the teams. As such, an assumption of these robotic competitions is that autonomous service and assistive robots need to be powerful enough to navigate and operate efficiently in a world that is not designed for them. Understandably, no further consideration is given to the space or furniture, which are simply referred to as “a realistic home setting... built up using standard fair construction material”. In RoboCup@Home, the intent is to focus every year on “more and more on real applications with a rising level of uncertainty”. This search for increasingly complex and powerful robots is in contrast with the stated reward for cost-effective robots, and the guideline that testing scenarios “should be low in costs”. Notably, the RoboCup@Home committee precludes adaptations and modifications of the environment aimed at reducing the computing resources and hardware requirements for social robots.

In the robot-inclusive challenge, five areas are identified for the design of robot-friendly spaces, i.e., observability, accessibility, manipulability, activity, and safety (Mohan et al., 2015). Robot ergonomics builds on that work by focusing on manipulability to develop and demonstrate a designerly approach to the design of human-centred and robot-inclusive environments and objects. Three related research directions developed in recent years include: Architectural Robotics (Green, 2016), Programmable Matter (PM) (Goldstein et al., 2005), and exhaustive surveys of everyday tasks (Jain et al., 2010). Our work departs from those approaches in fundamental ways. Whilst the aim of Architectural Robotics is to create buildings and even neighbourhoods that reconfigure their form on demand, Robot Ergonomics seeks to minimize the complexity, costs, and computational demands of the system. Rather than viewing the built environment as a robot, Robot Ergonomics defines robots as target users. In PM the aim is to build reconfigurable physical artefacts from nano-scale modules, leading to completely shape-shifting robots that could adapt to any environment. Whilst ambitious, this puts the burden on the robots rather than considering their habitat. Exhaustive surveys of kinematic trajectories and forces aim to model the requirements and constraints for robot design. Robot Ergonomics defies the belief that individual robots or assemblies of robots should bear all the responsibility for full functionality in environments that are designed with no regard to their capabilities and limitations. Instead, the idea is that designers across areas engage in dialogue and share responsibility for designing usable, efficient and safe systems of synergistic spaces, products and robots.

The design of handles is selected here to illustrate Robot Ergonomics for two key reasons: first, they are the quintessential *interface* product as their purpose is to facilitate the operation of other products rather than being end products by themselves. Second, handles are prominent in skilful manipulation tasks as defined by the briefs of prominent social robotics competitions, in particular the Domestic Standard Platform League (DSPL) where the goal is to assist humans in a domestic environment (RoboCup, 2016). Tackling the “handle problem” is likely to significantly contribute to the operation and value of social robots. Guidelines exist today to inform the design of handles based on a thorough understanding of the human hand, wrist, and arm (Mackenzie and Iberall, 1994). Nonetheless, handles are often selected as exemplars of poor designs that confuse, challenge and exclude large groups of users (Norman, 2013). A conventional classification of handles is based on the type of grip required by the adult human hand, but many other schemes exist (Lee, 2005). Studies that compare the design of robotic hands and handles are lacking, despite an awareness that some of the lessons learned from ergonomic studies of handles “will help plan or improve the working relationship between robots and materials” (Patkin, 1997).

### 3. Design for diverse humans and robots

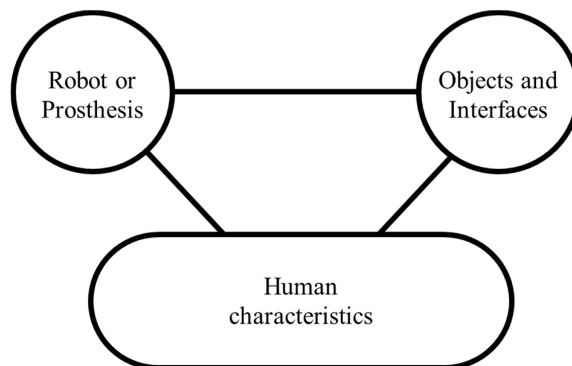
The fundamental paradigm underlying Robot Ergonomics is the notion of "coupling" between a robot and its surrounding objects and spaces. The Function-Behaviour-Structure design framework (Gero, 1990) helps to demonstrate what we mean by "coupling". In current practice, design decisions are disconnected and therefore a function such as <open door> is achieved by two separately designed structures which perform uncoupled behaviours. On the one hand, objects and environments are configured to behave or perform in ways that are appropriate for human dimensions and capabilities; on the other, robots are designed to approximate the highly diverse, adaptable, and efficient performance of fully-abled humans. Robot Ergonomics seeks to integrate the behaviour derived from the structure of everyday objects and spaces with that of social robots. The goal is to coordinate design decisions across areas to achieve designs whose structures are shaped by a shared set of compatible behaviours to work in synergy to perform the desired functions.

Coupling helps to align the capabilities of robots with their environments. This integration can be symmetrical or asymmetrical. By symmetrical coupling we refer to features in the robot and in the environment or products manipulated by the robot that are designed to symbiotically take advantage of each other. An example would be to select matching features in the type of flooring materials and finishes in a building and the type of robot locomotion (wheels, legs, or tracks). Asymmetrical coupling consists of one of the two elements being used to drive the design of the other, i.e., the use of landmarks and markers to specifically guide robots.

Functional Analysis is a design method that is particularly suitable to coordinate conceptual design decisions across domains and achieve coupling (Stone and Wood, 2000). In functional decomposition, lower-level functions are identified between robots and the spaces and objects that they manipulate. For example, in the design of a door handle and a robotic or prosthetic hand, the design team may identify <grip> as a low level function to achieve the higher level function <open door>. Rather than conceptualise design ideas to achieve <grip> in isolation for the robot hand and the door handle, the design team would consider how both can complement each other to increase the <grip> sub-function in conjunction. Coupling can lead to reciprocal features that are visible or hidden from view.

#### 3.1. Design principles of Robot Ergonomics

Considering three constitutive directions for Robot Ergonomics as shown in Figure 1, we propose design principles and design approaches for human-centred and robot-inclusive design. Prostheses are considered mostly as robots manipulators due to their limited mechanic properties closer to robot hands rather than human hands in terms of dextrous capabilities (Belter et al., 2013).



**Figure 1. Directions in Robot Ergonomics: Human, robot/prosthesis, and objects**

The following Robot Ergonomics principles were inductively extracted from the cross-disciplinary collaboration in design and robotics (Sosa et al., 2014; Mohan et al., 2015; Nansai et al., 2015; Tan et al., 2015).

1. **Priority:** Human needs and characteristics work as the "anchor" in Robot Ergonomics. The human body defines the solution space by settings the range of possibilities given its physical dimensions but also its aesthetics, semantic, and cultural characteristics (Krippendorff, 2006).

For example, since the (biological) human hand varies considerable in sizes and functions, design teams consider what type and range to select as a baseline (age, gender, and percentile measurements). As a rule of thumb, the 95th percentile is useful to define length and width, whilst the 5th percentile is appropriate to define strengths and heights. Overall, designers must consider that the harder it is for a human to operate, the harder it will be for robots.

2. **Explicitness:** Humans are highly adaptable and are highly experienced living in the world. As a result, designers often rely on common-sense to define design features. When designing with robot users in mind, it becomes imperative to design for a complete and exhaustive sequence of fully explicit actions, i.e., objects that are meant for robot manipulation must account for visual recognition; expected function/use models; physical approach including direction, orientation and reach; contact; operation; balance; release; and learning.
3. **Integration:** Objects, robots, and prostheses need to be designed with consideration to objective and quantitative criteria (dimensions, weight, force), as well as qualitative criteria such as sensorial qualities and cultural conventions of the built environment to which they are designed for (Bordegoni, 2011; Huang and Kang, 2017).
4. **Appropriateness:** Robots and prostheses are multifunctional, they are meant to operate a range of devices and they also have expressive functions such as gestural communication. Due to such richness in their appearance and functional dimensions, the design artificial hands cannot be optimal, there will always be a range of more appropriate solutions as judged and presented through a design argument (Siegel and Stolterman, 2009).
5. **Reconfiguration:** Reconfiguration principles including shape-shifting may be used to integrate functions in objects and spaces as well as robots and prostheses (Sosa et al., 2014; Tan et al., 2015).
6. **Simplicity:** Design decisions across areas must prioritise simple solutions in both objects and robots. Complexity needs to be minimised and design decisions need to pursue resilience, long-term adaptability including to new technology and new social perceptions, and graceful degradation. Whilst robots may evolve in shorter time spans than their environments and change significantly in the future, if their hands are well adapted to our everyday world, these body parts can reach stasis. This principle echoes two of the influential design principles postulated by the renowned designer Dieter Rams, i.e., long-lasting and as little as possible design.

These design principles are of high relevance for human-centred and robot-inclusive design, and design teams will need to incorporate a host of general design principles from their areas of expertise. Tensions and trade-offs between these principles are to be expected in the design of human-robot systems. Techniques that can be used to achieve coupling include the use of visual markers (QR codes for example) not merely as an easy way out (RoboCup, 2016), but as a mechanism to allow robots to learn, reinforce, adapt, and share information about the functions of objects and spaces, and the working status of specific instances. In order to apply these principles, we propose three complementary design approaches, and focus on the third one to present a case study where these principles are applied in the coupled design of door handles and robotic hands.

## 3.2. Three design approaches

### 3.2.1. Robot-to-Object

This design approach takes objects and environments as defined, and sets to design new robot features and capabilities to operate and fit in their environments. This approach will tend to produce asymmetrical couplings since the robots need to leverage on the features of the objects and spaces already designed. A typical example is the RoboCup@Home competition (RoboCup, 2016) where the challenge focuses on enabling a robot to operate conventional living spaces.

### 3.2.2. Object-to-Robot

This approach takes robots as defined and sets to design new objects and environments that suit certain types of robots. This approach will tend to produce asymmetrical couplings too, since the

objects and spaces need to leverage on the features of robots. A typical example is incorporating ramps for wheeled robots to access a space.

### 3.2.3. Robot-and-Object

This approach takes both robots and objects and environments as precedents, and sets to design new versions of both in ways that inform each other. Rather than aiming to design specialised pairs of robots and objects or environments, the goal here is to design for a range of types of robots and a range of types of objects. To illustrate the design principles using this approach, we focus on the criteria and heuristics that a design team would need to consider in order to design both robotic hands (or prostheses) and door handles.

## 3.3. Types of hands

Human hands vary considerably in dexterity: from those affected by rheumatoid arthritis or other health conditions and injuries, hands of small children and the elderly, a variety of situations such as soapy hands, people unfamiliar to the task or from an outside culture, all the way to fully able adults – which still vary significantly in sizes and capacities (Dellhag and Bjelle, 1999; Duruöz, 2014). A transition type between human and robotic hands are prostheses, ranging from simple passive and cosmetic to body-powered and the most sophisticated myoelectric which require intensive training.

The focus here is on robot hands, and specifically the hands of the Toyota HSR platform because this is what the Domestic Standard Platform League (DSPL) prescribes for the competition (RoboCup, 2016). Other types of robotic hands and prostheses can be considered, including simple metal hooks as a simple passive end effector. A hook mechanism mimics the use of a single finger to peg around a handle and pull. Hooks are passive, low cost and low maintenance, they can be sturdy, and vary dramatically in diameter, rod and overall size, bent angle, etc. (Belter et al., 2014). A hook can be linked to the robot arm with a rotational joint. Hooks are suitable for miniaturisation whilst remaining low cost and low complexity. Strength is an advantage of hooks, while dexterity is a disadvantage. Hooks are usually rolled rods, but they can also be extruded in order to maximize contact area for improved grip and overcome the lack of localized actuators. Up/down, push/pull and twist movements are achieved by the robot wrist and arm. Autonomous tool change is possible where the robot carries a variety of hooks and detaches/attaches them to increase its functionality.

Fingered grippers have two or three fingers. Such fingered grippers often use friction to handle an object. To achieve greater friction, fingered grippers are often fitted with skin surfaces made from polyurethane. Robot grippers or claws have a wide variety of dimensions and characteristics. Common grippers use four-bar linkages to operate two or three tongs actuated by a single pneumatic or electric step-motor. To transmit motion, gears or spring and cables are employed to open/close the gripper. The choice of bars and joint materials, motors and mechanisms has a direct impact on the strength of a gripper, and the dimensions and range of movement determines its dexterity. Low cost and simplicity are its main strengths, whilst torque and dexterity are key disadvantages. With two or three opposable digits, grippers are widely used for basic grasping functions and in certain configurations they can fit in tight spaces and be lightweight (Monkman et al., 2007). However, the lack of movement at the finger level considerably limits its grasping abilities.

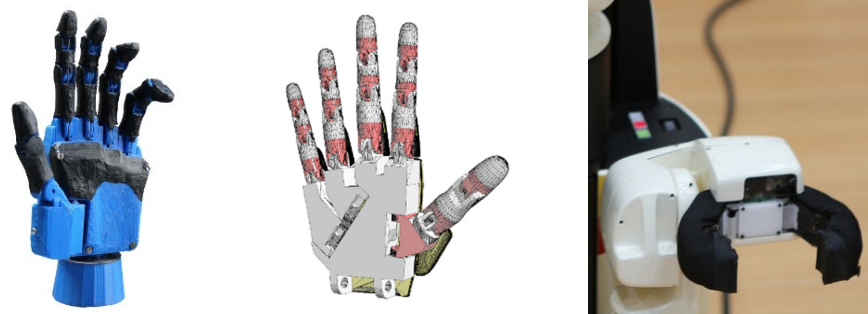


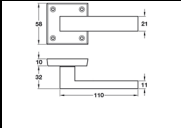
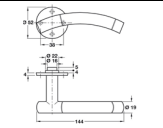
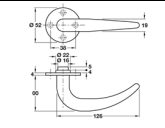
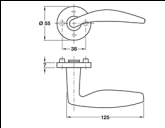
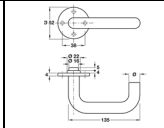
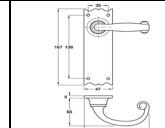
Figure 2. Open Hand® prosthesis; InMoov® robotic hand; Toyota HSR® gripper

Prehensile grippers or hands are anthropomorphic multi-fingered end effectors that allow for highly dexterous manipulation. In prehensile grasping, the objects motion while being grasped is assumed to be fully constrained by the gripper with minimal need for environmental interactions or support. Robotic hands are the more diverse end effectors in robotics, with embodiments of up to a dozen degrees of freedom, and multiple motors for individual flexion of fingers and phalanges. Robotic hands are the norm in anthropomorphic robots and can usually adjust a variety of forces, positions, and some include force sensing feedback. Size and other characteristics are conventionally modelled after the human hand. Whilst dexterity and force are strengths of robotic hands, cost and complexity are their main disadvantages. Projects such as “Roy the Robot Hand” propose low-cost and simple robot hands made from laser cut parts and inexpensive servos (Roe, 2017). From an ergonomic viewpoint, robotic hands like Roy offer multiple contact points and over a dozen degrees of freedom, which translates into relatively advanced dexterity –arguably close to a human arthritic hand. In the following section, the Toyota HSR hand and the Häfele handles are analysed as precedents for the design of robotic hands and door handles to show how a design team can target the coupling of robots and objects.

#### 4. Validation

A classification of handle design distinguishes four main categories according to the type of grip required by the human hand: power, pinch, precision, and skilled grip (Patkin, 1997). We analyse a catalogue of door handles using a morphologic approach to characterise the type of handles available commercially. The Häfele catalogue is chosen for clarity although some designers may regard this type of catalogues directed to cabinetmakers –the principles, however, can be applied to any collection of handles including artistic and architectural archetypes. Five main types of door handles are inductively extracted from the catalogue by two experienced industrial designers from 96 models based on the shape profile and their dimensions. The five main types of door handles identified are L-Shape, C-Shape, pulling, pinch and knobs. the first three types fit the requirements of power grip, i.e., “fingers bunch firmly around the object, overlapped by the thumb; handle is thick enough to separate finger-tips from the palm; a large area of contact is possible” (Patkin, 1997). Handles of pinch type fit the requirements of pinch grip, i.e., “the thumb and the side of the index finger are used for picking up small objects” (Patkin, 1997). We focus here on L and C-Shape handles because they group a majority of models (70 of 96), and further differentiate the following subtypes: Right angle, Curved, and Organic for L-Shape handles. Curved L-Shape handles are further divided into Front and Top variants indicating in what projection view is the curve defined. C-Shape handles are divided into Regular and Irregular extrusions. Table 1 shows this classification of door handles.

**Table 1. Canonical representation and reference image for squad and hook types**

L-Shape				C-Shape	
Right angle (28)	Curved-Front (4)	Curved-Top (15)	Organic (10)	Regular extrusion (8)	Irregular extrusion (5)
					

A dimensional analysis of Häfele door handles is summarized in Table 2 that includes the average (mean), minimum (min), maximum (max), and variance (var) values for the handles’ inner length (X), the handles’ height (Y) and the distance between the handle and the wall or vertical surface (Z) as specified in the product catalogue. These values are used in the next section in order to carry a comparative analysis of robotic hands and commercial door handles based on ergonomic principles. The focus here is on initial results to apply Robot Ergonomics as a cross-disciplinary design approach.

**Table 2. Average (mean), minimum (min), maximum (max) and variance (var) values X, Y and Z**

Type	Subtype	X mean	X min	X max	X var	Y mean	Y min	Y max	Y var	Z mean	Z min	Z max	Z var
L-Shaped	Right angle	109.8	92.0	132.4	64.0	18.5	10.2	28.8	25.4	45.9	28.2	54.5	31.5
	Curved-Front	106.5	102.7	111.0	11.5	16.4	12.5	19.0	7.7	44.6	41.8	47.2	3.9
	Curved-Top	88.3	65.8	110.8	169.1	16.6	13.7	21.9	5.7	30.7	17.5	40.0	26.3
	Organic	100.5	91.6	105.7	19.3	14.6	11.2	25.0	13.0	39.0	29.9	46.1	37.2
C-Shaped	Regular extrusion	95.3	93.2	99.9	3.8	19.6	19	20.0	0.2	51.8	47.7	57.1	10.1
	Irregular extrusion	56.3	53.3	66.8	27.6	16.5	15.2	21.0	5.1	53.1	47.0	55.2	9.5

#### 4.1. Heuristics for the design of robotic hand and door handle

A systematic analysis of the geometry of door handles and the Toyota HSR gripper was conducted considering its dimensions, hand operation area, and shape features. The Toyota HSR two-fingered gripper is shown in Figure 3; its dimensions are: height = 78.4 mm; width = 44 to 280 mm; and depth = 66.6 mm. Its opening range is of 236 mm. Our baseline for comparison are male and female adult right hands without mobility constraints.



**Figure 3. Toyota HSR® two-fingered gripper dimensions**

Regarding the horizontal dimension (X axis) of door handles (length), based on the Toyota HSR dimensions, the handle's length should be between 100 and 150 mm so that it can be easily grasped by an adult male hand (Lee, 2005). Anthropometric data reveals that the 95th percentile for male's hand breadth is 97.03 mm while the 5th percentile for women is 76.96mm (Buchholz et al., 1992). As the "X mean" column on Table 2 shows, the dimensional requirements for a grip breadth manipulation of an adult hand described above are fulfilled only by three subtypes of handles: Curved-Front, Right angle and Organic. In contrast, as the HSR gripper can open up to 236.8 mm, the robot would be able to grasp any of these handles from side to side and then rotate its wrist to activate them. However, as the contact surface between the HSR's hand and the handles is drastically reduced in this type of grasp, traction between the robot hand and the handle will be a critical variable in the performance of such task. As they provide the largest contact surface of all, the Right angle and Regular extrusion subtypes are the most suitable handles for this kind of gripping.

Regarding the vertical dimension of door handles, based on the HSR dimensions, the mean handle's height ("Y mean") column of Table 2 shows that all subtypes have heights below 20 mm. Considering that the 5th percentile for the length of females' fully extended thumb, index finger and middle finger are respectively of 53.85 mm, 69.09 mm and 77.98 mm (Vermaas et al., 2013), none of the handle subtypes present ergonomic disadvantages for human users. Similarly, given the distance at which the Toyota HSR gripper can be opened, all the handles could be easily grasp by the robot. Therefore, the



handle's height could have a maximum diameter of 400 mm to allow the thumb to cover the end of the index and middle fingers of an adult hand (Patkin, 1997).

The operation area of a door handle is defined here as the gap or space between the handle and the door. This area is critical to facilitate hand access, avoid potential finger damage, avoid awkward postures, and maximize visibility and usability. Since the length of the index finger's proximal phalange for the 95th percentile of males is 47.37 mm, hook handles offer the best grasp. However, since the 95th percentile for the male's hand breadth (97.03 mm), is greater than the inner length of both hook subtypes, they appear as suboptimal. With a depth of 66.6 mm, the Toyota HSR gripper can in principle grip the handle, however the available space between the handle and the wall or vertical surface is insufficient to enable adequate operation.

Shape-wise, no sharp edges should exist in the grip area because they can decrease the comfort, strength, and security of gripping (Patkin, 1997). An enlargement or bend at the end of the handles can help avoid slipping, which could occur due to momentary relaxation of grip or while turning the handle (Patkin, 1997). Such characteristics are present in the Organic, Regular extrusion and Irregular extrusion handles of the Häfele catalogue. Since the HSR's fingers do not adapt to the shape of the objects they hold as precisely as the human hand does, these volumetric variations might compromise the stability of the robot's grip due to a decrease of the contact surface between its hand and the handle. Because of this, the HSR's gripper is likely to perform better when manipulating handles with volumetric regularity as in the cases of Right angle and Regular extrusion subtypes.

Based on these metrics, a compatibility assessment between the Toyota HSR gripper and the Häfele handles helps to identify the critical features and dimensions when designing door handles for grippers. Notably, the vertical dimension of door handles and the operation area (gap) are the least critical dimensions, whilst the horizontal dimension and the shape of handles can be highly critical. This analysis shows that the most suitable door handles for the HSR hands are the Right angle and Regular extrusion because they enable the gripper to approach and grasp horizontally or vertically, depending the position of robot and handle. The regular shape of these handles increases the contact area and firmness of the grip. However, these subtypes fail to provide enough space for the HSR gripper to approach and grip from above. All other subtypes are considered inadequate because they afford only vertical approach and partial gripping. A compatibility matrix is proposed in Table 3 showing two levels of compatibility (low or high) for each dimension of the Häfele handles and the Toyota HSR gripper.

**Table 3. Toyota HSR compatibility with Häfele's L-Shaped and C-Shaped handles**

Handle subtype	Horizontal dimension	Vertical dimension	Operation area	Shape
Right angle	High	High	Low	High
Regular extrusion	High	High	Low	High
Irregular extrusion	Low	High	Low	Low
Curved-Front	Low	High	Low	Low
Curved-Up	Low	High	Low	Low
Organic	Low	High	Low	Low

Whilst these results are specific to the HSR's gripper, the insights gained can provide a reference for evaluating other types of robot hands. For example, the lack of surrounding space that so severely affects the HSR gripper could also affect the performance of other robot platforms aiming to become standard social and service robots. Particularly, anthropomorphic robot hands have serious limitations. For instance, the Aldebaran Nao's hand (Gouaillier et al., 2009) which is partially covered by a protective case is not optimally designed for manipulation of everyday objects.

Such limitation can be exacerbated by the reduced size of the Nao's fingers. Taking these particular features into consideration, the most suitable handles for the Nao might be those characterized as Regular extrusion. Besides enabling the robot to cover the end of its index and middle fingers with its thumb, the twist at the end of this subtype of handles would provide a mechanism to avoid slipping.

Considering the width of the Nao's hand, this last feature might be a decisive factor during its door opening attempts.

## **4.2. Design directions to couple human and robotic hands, and door handles**

We describe a set of design directions to achieve an adequate coupling between robot hands and handles. These come from extensive discussions between industrial designers and roboticists guided by the design principles presented in this paper. Points of agreement from these discussions are clustered and summarised below.

### *4.2.1. Object morphology for symmetrical coupling*

To extend the compatibility of door handles with both human and robot capabilities, we propose that cross-disciplinary design teams:

- Design handles of rounded or square section applied to Right angle and Regular extrusion-type morphologies to extend the contact surface and thus increase the steadiness and strength of the robot's gripping.
- Organic-type handles could incorporate plain ends on the horizontal axis to extend the contact surface and thus increase the steadiness and strength of the robot's gripping. Likewise, rounded handles could have an increased height (closer to the base attached to the wall or vertical surface) to extend the contact surface and thus increase the steadiness and strength of the robot's gripping.
- Design handles with an extended separation from the wall or vertical surface so that robot hands can easily approach and grasp them from above. Such configuration could be an improvement for other anthropomorphic hands, hooks and low-tech prosthetics with more limited manipulation capabilities that require different approaching angles to move and turn the handle.
- Handles with 5th percentile female dimensions with limited dexterity (maximum grip diameters = 34mm) would suit a sizeable proportion of human users as well as variety of robot actuators (McLain, 2010).

### *4.2.2. Robot morphology for symmetrical coupling*

Whilst service and social robots tend to replicate human movements, they could have a different range of movements as determined by their actuators. Hence, we propose that cross-disciplinary design teams:

- Design robot hands with the capacity of extending beyond 150 mm in the X axis to align with the features of a wider variety of handles. Whilst this is not a natural human movement, it can be an energy saver and preserve the mechatronic systems in robots.
- Design robot hands with plain fingers to align with the features of handles of rounded square section. A critical factor is to reduce the dimensions of the surrounding case in robot hands as much as possible.
- Design robot hands that can grasp rounded and cylindrical shapes to increase compatibility with Organic-type handles and a superior height in relation to the handle base and the wall or vertical surface.
- Robot hands of larger sizes (95th percentile male hand length = 205 - 209mm; palm length = 116mm; hand breadth = 95mm) can adapt to a variety of handle dimensions and have more operational room around the handle in multiple approaches (McLain, 2010).

In the design of robot hands and door handles, an iterative process progressing across the following stages is suggested: start with low-fidelity prototyping of handles and robotic hands using strategies of physical simulation to gain early insights about the design issues affecting the coupling between components. Computer-Aided Design can be used to study dimensional compatibility between human and robot hands and door handles, including techniques such as collision detection. More advanced physical and virtual testing can inform the design decisions leading to 3D additive manufacturing prototypes. Further factors are involved in the symmetrical coupling of robots and objects. The study case presented here is an exploratory study to illustrate design guidelines rather than an analytic

extensive study aiming to provide evidence to support the joint design of handles and robot hands. In addition, other factors to be considered include the aesthetics and semiotic dimensions of these products. In the case of robot-inclusive objects, the product semantics include clues about their function and use (force, momentum, opening direction) to both robot and human users. Sustainable solutions for robot ergonomic guidelines should be prioritized.

## 5. Discussion

This paper presents a case study of door handles and robot hands to illustrate a novel cross-disciplinary approach to the design of robots, the environments they will inhabit, and the objects they will operate in the future. We limited our study to a dimensional analysis since the aim is to illustrate the principles of Robot Ergonomics. Further analyses are required in the design of robot-inclusive products and spaces including effort analysis such as The Grip Ability Test (GAT) and the Keitel Function Test (Dellhag and Bjelle, 1999). Likewise, mechatronic analyses would similarly extend the design guidelines suggested here (Belter et al., 2013).

New questions for future research that emerge from this initial work include that if future robots use unsupervised learning techniques to learn how to manipulate objects, they could in principle become highly adaptable to their environments through trial and error as well as by incorporating instructions learned by other robots interacting with similar devices. A range of ethical and sustainability related issues also become apparent. Namely, by reversing robot-inclusive principles and tactics, it would be possible to define areas designed to be off-limits to robots. In addition, the design of robot-inclusive environments could accelerate obsolescence of current objects and spaces with the negative consequence of increased waste. Moreover, the goal of Robot Ergonomics is to facilitate robot functions by simplifying the entire system, but this fails to address the actual purpose of deploying social or service robots in the first place -and the societal impacts of doing so.

In the future, lessons learned from Robot Ergonomics can be applied to other domains and technologies such as the design of exoskeletons and human augmentation. Technologies such as soft robotics in manipulators and electrophysiological (EEG) control would present new opportunities and challenges to cross-disciplinary design teams that could build upon and extend Robot Ergonomics.

The approach presented here demonstrates the importance of studying the rationale for the design of robotic hands. Everyday product catalogues categorise objects by aspect or material, however they fail to offer recommendations based on users' abilities. This paper explored how roboticists and designers can collaborate to decide what types of robots and what types of objects and environments to design. The analysis presented in this paper needs to be complemented with future empirical studies including experimental and qualitative approaches. Experimental ergonomic setups are being devised to benchmark robot embodiments to design a friendlier and more sustainable environment for humans and robots.

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