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A Methodology for early design specifications of robotic grippers.

Jonatan Martín Escorcia-Hernández [1], Mathieu Grossard [1], Florian Gosselin [1].

***Abstract*—The objective of this article is to present a comprehensive task analysis methodology that can provide guidelines for the design of dexterous robotic grippers. This methodology combines a human-centered gesture analysis and an object-centered grasp stability analysis. The former relies on a careful examination of a human operator's hands gestures while performing a specific process, providing designers with tools that help specifying the number of fingers, the number of degrees of freedom, and the placement of tactile sensors. The latter exploits a grasp quality metric to compute the efforts required to handle the involved objects, providing guidelines for the specification of the actuation system. This approach is exemplified by defining technical specifications for the design of a multi-fingered robotic gripper intended to perform the tasks involved in a sterility testing process.**

***Index Terms*—Human-centered gesture analysis, grasp stability analysis, design specifications, multi-fingered grippers**

I. Introduction

The design of dexterous multi-fingered grippers is a challenging task as a large number of factors must be considered for their successful manufacture. According to [1], the success in designing a gripper is determined by six main design factors, which are the kinematic architecture, the actuation, transmission system, materials, manufacturing, and sensing. A key aspect of the design process is to define certain kinematic, mechanical, and sensing characteristics that the future gripper must satisfy in order to successfully perform the target activity. Many grippers designs take the human hand as a reference [2], [3]. However, the realization of a grippers with a high degree of anthropomism turns out to be very complex due to the complexity of the required mechanisms, the large number of actuators, the coupling between some DoFs, and highly nonlinear dynamics, among other issues [4]. These limitations have led to the proposal of simpler designs that, consequently, have a lower degree of anthropomorphism. Designing a simpler gripper that diverges from an anthropomorphic approach does not mean that it has less dexterity [5]. According to a study of human-hand gestures, a human operator uses multiple types of grasp patterns but only a few of them are employed more than 80% of the time when accomplishing tasks [6]. So, one can infer that for specific human activities, we can rely on a human-centered gesture analysis to identify the most commonly used grasps and propose architectures of multi-fingered robotic grippers designed to perform a specific procedure. Regarding the grippers design methodologies found in the literature, we can highlight those proposed by: Honarpardaz et al. [7], in which they summarize the finger design process for grippers into three global stages: (i) synthesis and analysis of the grasp; (ii) finger design in function of the grasp information and collision detection, and (iii) experimental verification of the gripper design. Puig et al. [8] introduced a design methodology consisting of the following steps:(i) problem definition, (ii) concept design, (iii) preliminary design, and (iv) design communication. Data-driven grasp approaches have also been used to optimize certain parameters of grippers. They consider quality metrics, which are used for evaluating the quality of the grip taking into account multiple ways to grasp a set of objects [9], [10]. Even though the methodologies described above offer guidance for the design of the gripper itself, they lack a solid basis for defining the design specifications. In other words, answer the following questions: What is the optimum number of fingers? What dimensions should each finger have? How many degrees of freedom? Where to place touch sensors? What amount of force/torque should the gripper provide in order to perform a specific procedure? This research aims to present a novel methodology to rationally define such specifications for multi-fingered robotic grippers (i.e. number of fingers, number of phalanges per finger, kinematic configuration, dimension of mechanical elements, placement of tactile sensors, and the specifications for the actuation system). Our proposed approach relies on two main studies: *A human-centered gesture analysis* which is inspired by ergonomic-based grasps classifications and used to set the kinematic structure parameters. And *an object-centered grasp stability analysis* used to determine the force/torque that the actuation system of the gripper must provide to accomplish the task for which it is designed. The proposed methodology is intended to allow specifying optimized multi-fingered grippers that are sufficiently versatile to perform specific sets of tasks with a high degree of dexterity, yet simple enough for an efficient mechanical design. In the literature, researchers have tried to address this problem by proposing systematic methodologies, some of them are discussed in the following subsection. The remainder of the paper is organized as follows. Section II describes in detail the steps that comprise the Human-centered gesture analysis, the Force-based grasp stability analysis is performed in Section III, Section IV discusses the technical specifications of the future gripper, and finally, the conclusions of this paper are addressed in Section V.

[1] J.M. Escorcia-Hernández, M. Grossard, and F. Gosselin, are with Université Paris-Saclay, CEA, List, F-91120, Palaiseau, France. Emails: {jonatan.escorcia, mathieu.grossard, florian.gosselin }@cea.fr

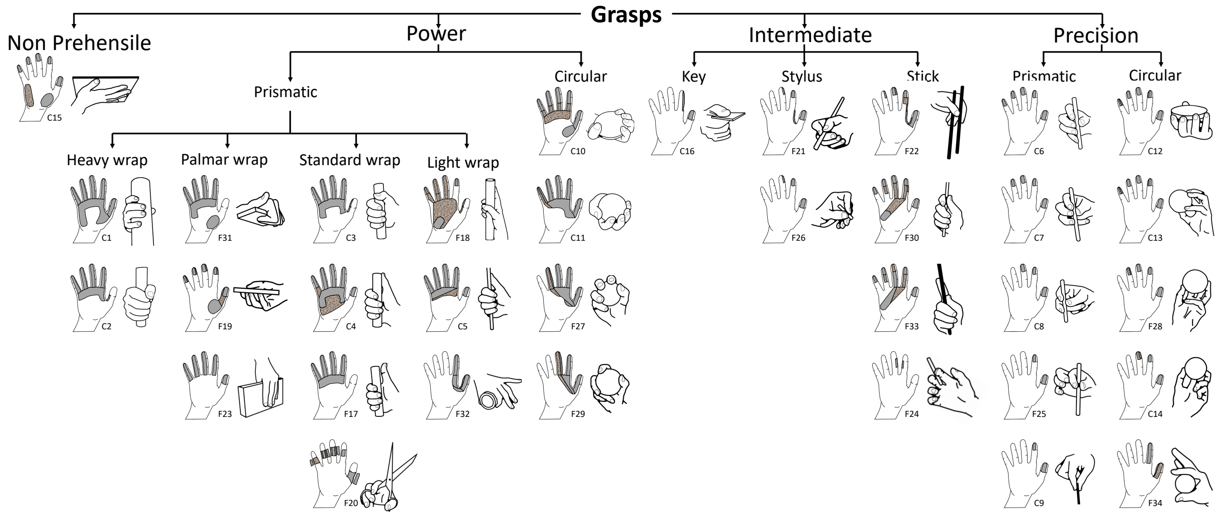

Figure 1. The Cutkosky and Feix grasp taxonomies with their corresponding hand-object contact surfaces representation.

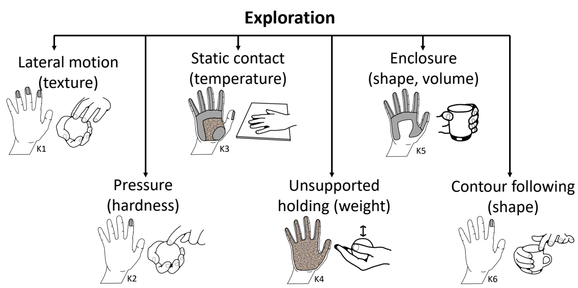

Figure 2. The exploratory gestures' taxonomy derived from the work of Lederman and Klatzky with their corresponding hand-object contact surfaces representation.

II. Human-centered gesture analysis

This study begins with a detailed video analysis of the human hands-gestures used to carry out a specific process. In this article, it was performed on videos from a sterility testing process. In total, 12 videos covering the whole process have been analyzed. For a better understanding of the described use-case, the reader may address the following website: https://tracebot.gitlab.io/tracebot_showcase/root_index/.

A. Identification and classification of manual interaction patterns

The human grasps are traditionally organized in taxonomies the most often used being those proposed by Cutkosky [11], and Feix et al. [12], which are composed of 16 and 18 grasps respectively. Figure 1 shows their combined grasp classification. Each pattern is called Ci (with $i \in [1; 16]$) or Fj (with $j \in [17; 34]$) whether it is part of the Cutkosky or Feix et al. taxonomy respectively. These grasp taxonomies have also been complemented with the exploration taxonomy proposed by [13] and [14]. These exploration patterns are named Ki (with $i \in [1; 6]$) and are illustrated in Figure 2. However, there are certain grasps in our use case that do not fall into the previously mentioned classifications. To cope with these grasps, we introduced a novel grasp category called Ti. In practice, we identified 80 of those grasps (hence $i \in [1; 80]$). To describe them, we first drew schematic representations of each of them. The sterility testing process grasps are displayed in the taxonomy presented in Figure 3, being classified as non-prehensile, power, intermediate, and precision grasps similarly as in Cutkosky and Feix's work. In this figure, some contact surfaces are in red, which denote external support contact areas i.e. contacts external to the objects, such as the table.

B. Definition of hand-objects contact areas

The next step consists in identifying, for each interaction pattern, the hand-object contact area. For standard grasps types and exploratory movements, we refined the characterization of the contact areas compared to [15], [16] and [17]. We took in hand objects representative of the different usual grasps and we tried to insert a thin metal sheet between the hand and the object. We considered that the skin is in contact with the object only when we were not able to insert this tool between their surfaces. The results are depicted in the hand-object contact surfaces representation of Figures 1 and 2. For the specific Sterility testing process interaction patterns also, we tried to identify the hand-objects contact surfaces' as precisely as possible. As the gloves used by the operator do not always allow a clear vision of the way the objects are held, we reproduced the grasps with bare hands.

C. Identification of the frequency of use of each pattern

The frequency of use of each interaction pattern is obtained from a video analysis of the operators' gestures. As proposed in [6], several observers carefully look at the videos and identify the interaction patterns used by the operators. We note for each grasp the time it begins and the time it ends to be used. By subtracting the former from the latter, we get the grasp duration. It is worth noting that in practice, some grasps are used several times and/or with both hands. In such cases, we cumulate the

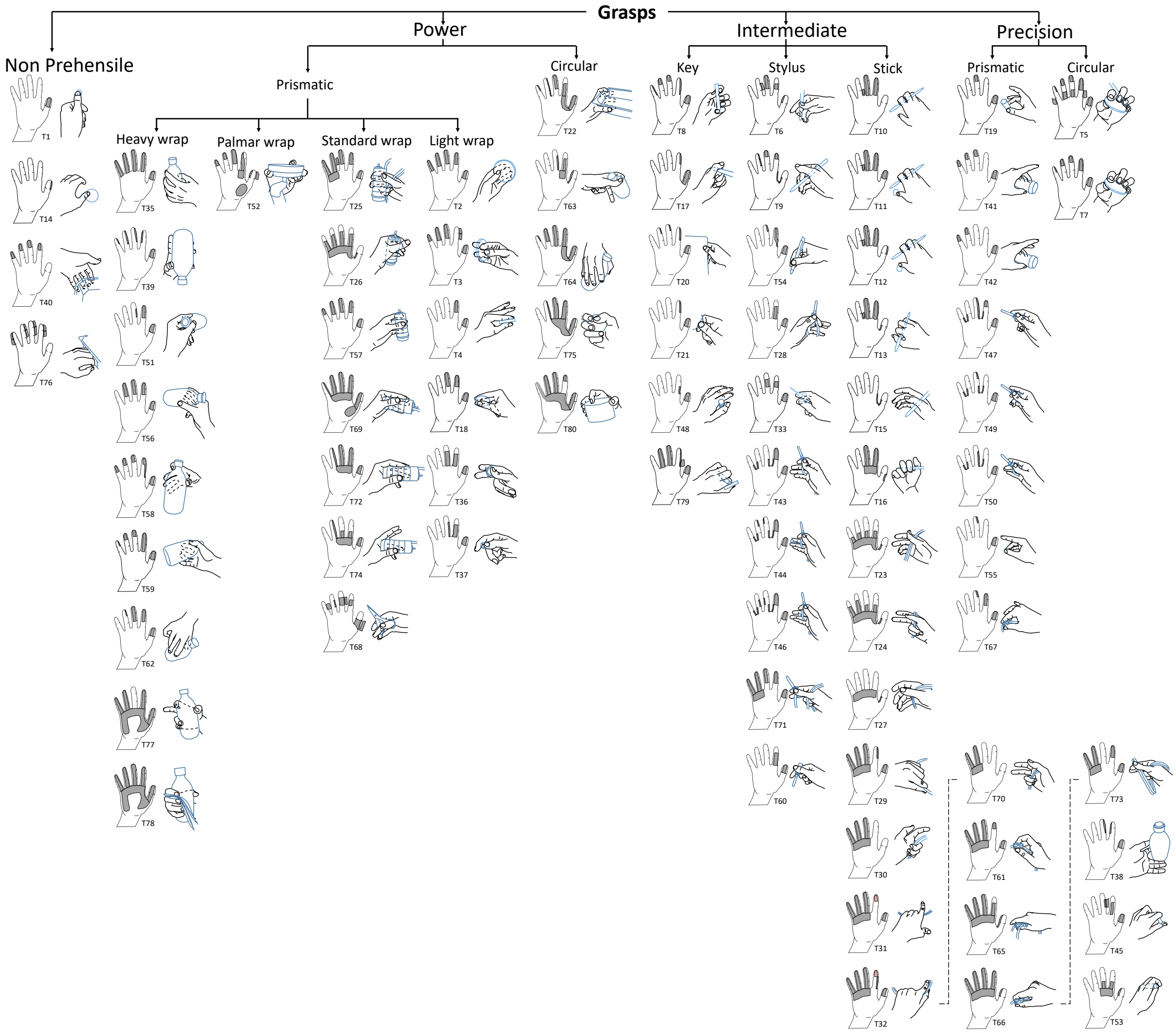

Figure 3. Use-case specific grasps' taxonomy with their corresponding representation of the hand-object contact surfaces.

times they are used over the whole process in order to get the total amount of time each grasp is used. These durations are further used to compute the relative frequency of use of the different grasps and interaction patterns, which is the duration of a given grasp divided by the duration of all grasps.

D. Identification of the directions of the forces applied by the hand

During the analysis of the videos, we also tried to identify the directions in which forces are applied on the hand. This analysis has to be made on each of the elementary hand areas as all areas may not be solicited similarly during a given manual interaction. The first step consists in setting a Cartesian frame on every phalanx (distal, intermediate and proximal) and on each area on the palm. Then several observers evaluate the direction(s) in which each area is solicited. It is worth noting that when coming in contact with an object to interact with it or grasp it, forces are first applied in the Z direction (normal to the skin). Then depending on the forces exerted on the object, forces may also appear in the Y and/or X directions (where X corresponds to the direction tangential to the skin in which palm and fingers extend, and Y is deduced from X and Z so as to have a direct frame [17]). As a result, Z is the most used direction when manipulating objects, followed by Y and X.

E. Generation of interaction maps

By associating the inner surface of the hand used to execute a given grasp or gesture with its frequency of use, we can get the frequency of use of each of the elementary interaction areas it is composed of in each direction. By overlapping the results associated with the different grasp types, it is possible to draw interaction maps. Interaction maps in Z (normal to the skin), Y and X (tangential to the skin) are provided in Figure 4. They give an overview of the way the hand is excited while performing the sterility testing dexterous activities. From these interaction maps, we deduce that the fingers' palmar sides are the most solicited areas, followed by the ulnar and radial sides of some fingers' phalanges. The ulnar and radial sides of the other fingers are much less used, as the dorsal side of the fingers and the palm. This tends to guide the placement of tactile

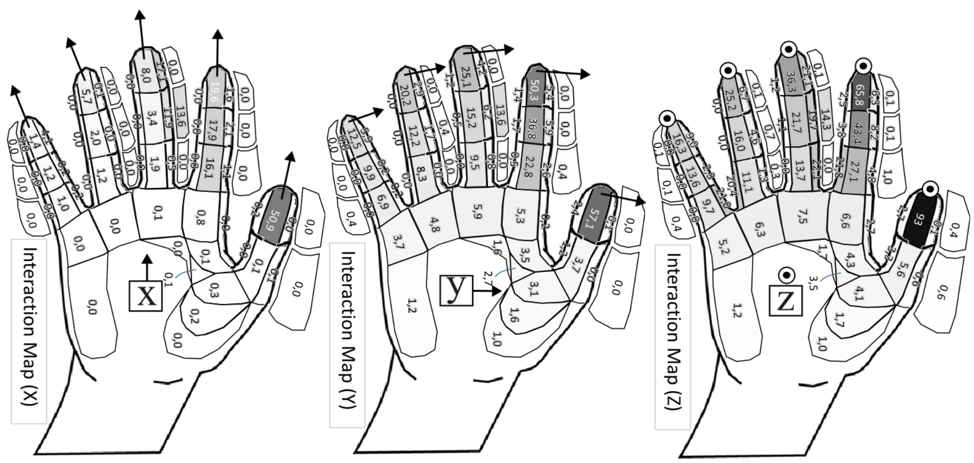

Figure 4. Resulting interaction maps of the use-case

sensors on the palmar side of the fingers, especially on their distal phalanges, and on the palm near the proximal phalanx of each finger, which are the most frequently used areas. Regarding the directions, we can see that the hand is mostly solicited in Z (i.e. normal to the skin). This highlights the primary importance of the fingers' flexion movements which, should be considered with care in the gripper's design. We can also see that the most used finger is the thumb, followed by the index, the middle, the ring, and the little, which is much less solicited than the other fingers. Based on these observations we can assume that a four-finger based configuration will be adequate for the design of the future gripper. Form these results we establish the kinematic specifications discussed in Section IV.

III. Force-based grasp stability analysis

A. Object-fingers contact model

Assuming an unique, well-defined, tangent plane at each contact point $\mathbf{c}_i \in \mathbb{R}^3$ between the finger and the grasped object, we can define a contact frame $\{\mathbf{C}\}_i$ whose axes are denoted as $\{\mathbf{n}_i, \mathbf{t}_i, \mathbf{o}_i\}$, with $\mathbf{n}_i \in \mathbb{R}^3$ defining the contact normal, directed towards the object and $\mathbf{t}_i, \mathbf{o}_i \in \mathbb{R}^3$ the tangential ones. The contact efforts locally transmitted at $\{\mathbf{C}\}_i$ will then be denoted by the static wrench $\mathbf{f}_{c_i} = [f_{cn_i} \quad f_{ct_i} \quad f_{co_i}]^T \in \mathbb{R}^3$, where $f_{cn_i} \in \mathbb{R}$ denotes the normal component of the transmitted contact forces, $f_{ct_i} \in \mathbb{R}$ and $f_{co_i} \in \mathbb{R}$ the tangential ones. Among the main contact types in grasping, we adopted the Hard Finger (HF) one in our study [18]. In such a case, contact forces are transmitted in the contact tangent plane following the inequality constraints:

$$\begin{cases} f_{cn_i} \geq & 0 \\ \sqrt{f_{ct_i}^2 + f_{co_i}^2} \leq & \mu f_{cn_i} \end{cases} \tag{1}$$

where μ defines the tangential friction coefficient between the finger and the grasped object, which may vary depending on several contact characteristics. The above standard sets of inequality constraints form a *friction cone* $\mathcal{F}_i$, that can be approximated by a polyhedral cone for an appropriate formatting for optimization, defined by a *local friction cone matrix* $\mathbf{F}_i$ in the following way [18] , [19]:

$$\mathcal{F}_i \approx \{\mathbf{f}_{c_i} \text{ s.t. } \mathbf{F}_i \mathbf{f}_{c_i} \geq \mathbf{0}\} \tag{2}$$

In the following sections, such approximation will be referenced to through the *global friction cone matrix* $\mathbf{F} = \text{blockdiag}(\mathbf{F}_1, \ldots, \mathbf{F}_{n_c})$, which allows to easily test the respect of contact types for all contact points n_c at once, through the following linear inequality:

$$\mathbf{F}\mathbf{f}_c \geq \mathbf{0} \tag{3}$$

Being $\mathbf{f}_c \in \mathbb{R}^{3nc}$ the vector containing all contact forces.

B. Description of the task quality metric

A specifically tailored task-oriented approach for grasp quality assessment is proposed as a new metric adapted to our class of problems. It is defined as *the magnitude of forces required at the hand-object contact locations to counter an external effort exerted at the center of the object frame*. One interest of this metric lies in its ability to provide insight into the to-be-designed gripper's ability to counter given external perturbations. It provides, for each identified object and each external effort considered in the Sterility testing process use-case, an estimation of the grasp force necessary to hold still the object. In practice, we denote by $\mathbf{d}_{W_{ext}} \in \mathbb{R}^6$ the fixed direction of the studied external effort refereed w.r.t the object reference frame, and its variable magnitude by $\alpha \in \mathbb{R}$, such that:

$$\mathbf{g} = \alpha \mathbf{d}_{W_{ext}} \tag{4}$$

reports for both forces and torques applied to the object (the last three components of $\mathbf{d}_{W_{ext}}$ will be normalized according to a characteristic length L of the grasped object). The magnitude metric is computed by resolving the following problem (P1):

$$\begin{aligned} \text{(P1)} \quad & \min \parallel \mathbf{f}_c \parallel_2 \\ \text{s.t.} \quad & \mathbf{G}^T \mathbf{f}_c + \alpha \mathbf{d}_{W_{ext}} = \mathbf{0} \quad \text{(Static equilibrium)} \\ & \mathbf{F}\mathbf{f}_c \geq \mathbf{0} \quad \text{(Friction cone)} \end{aligned} \tag{5}$$

where the grasp matrix $\mathbf{G} \in \mathbb{R}^{3n_c \times 6}$ maps the contact wrench given in their local frames onto the object frame. The proposed

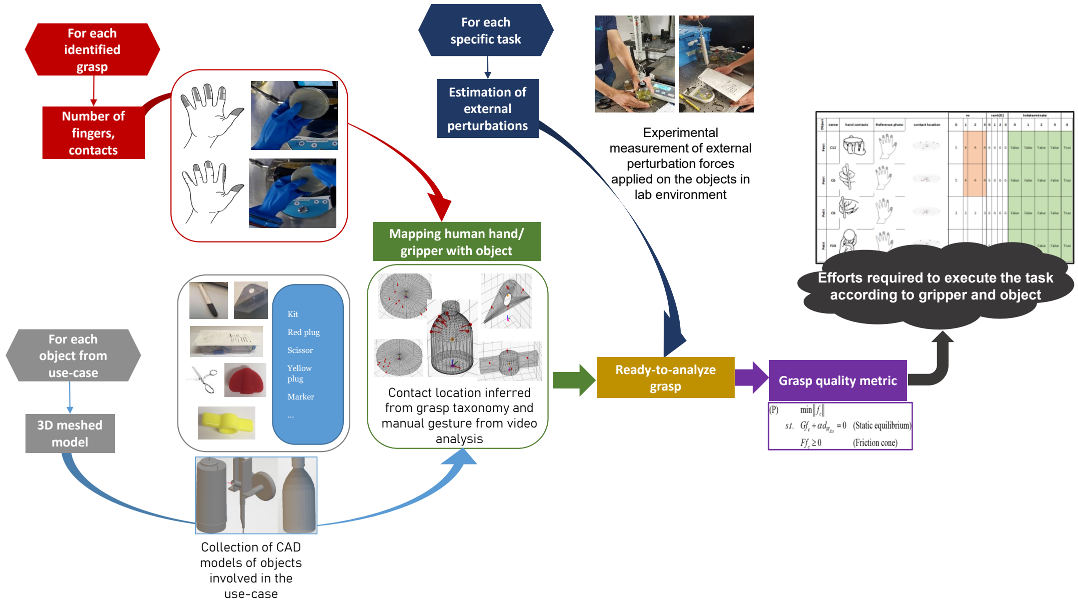

Figure 5. Global outline for grasp analysis methodology.

problem (P1) roughly embodies the mechanical limitations of the gripper actuators and helps finding the minimal requirement about the maximal force.

C. *Framework for grasp study*

The application of the previously presented grasp analysis tools on use-case objects is detailed below, each of the the four steps of the proposed methodology being illustrated in Figure 5.

1) Specifications: The grasp synthesis takes as inputs a batch of parameters, which help formulating the mathematical problem.

1) Firstly, a whole set of *object data* deals with the geometry, the inertial properties of each of the to-be-grasped objects, as well as their potential restricted areas.
2) A second set of data comprises the identified *external disturbances* (seen as external wrenches from a mechanical point of view) applied to each object involved in the task. These are related to inertia and gravity effects, as well as mechanical interaction forces that may occur between two objects during certain tasks (e.g. insertion or assembly).
3) Finally, a third set of parameters, also known as *grasp-type settings*, describe useful characteristics of the human or gripper grasp pattern: the number of fingers (including the palm) and the number of contacts (the contact type being chosen as HF for all fingers) as defined by each grasp pattern from the taxonomy. Table 1 presents the list of combinations between the grasp patterns and perturbations.

2) Mapping between human hand/gripper and object: First, a reconstructed meshed version of each object is done. Then, for each pair of grasp-type and object data, contact positions mapping the identified elementary contact areas of the human hand or gripper to the object are computed. All associated elements form a ready-to-analyze grasp.

3) Grasp stability analysis tool: A comparative tool is built: it is able to hold the grasp quality metric scores computed from (P1) for each ready-to-analyze grasp. The tool takes into account a multi-parametric analysis that includes all the combinations of parameters (object data, grasp type settings and external perturbations). Let note that, prior to solve (P1), each ready-to-analyze grasp is classified as "indeterminate or not" and as "graspable or not", based on the mathematical study of the grasp matrix $\mathbf{G}$ computed for each ready-to-analyze grasp: the analysis of the rank of the null space of $\mathbf{G}$ and $\mathbf{G}^T$ helps us understanding, from a control point of view, if the considered grasp allows to control all internal object forces and twists. The associated external perturbations have been estimated through physical measurements using the use-case objects.

4) Extraction of solution and derivation of design guidelines: The previously obtained analysis tool is post-processed to identify a satisfactory level of required forces at contact points resulting from the normal component of the applied force. The list of obtained metric values, computed from an object-centered point of view, happens to hold interesting insights concerning the required maximal force capability to be produced by the to-be-designed gripper considering a specific pair of object data and grasp type settings.

D. *Obtained results of grasp stability analysis*

A multi-parametric analysis that includes all the combinations of parameters (*object data*, *grasp type settings* and *external perturbations*) is used to generate and store force data for post-processing analysis. It helps better understanding the theoretical levels of effort that are required for achieving the use-case tasks. Among the useful extracted information, the

TABLE I
LIST OF COMBINATIONS BETWEEN GRASPS AND PERTURBATIONS CONSIDERED IN THE USE-CASE

Objects	Grasp type identified from taxonomy	Related perturbations
Petri dish	C6, C8, C12, F28, T2, T3, T4, T7, T8, T18	HOLD, WRITE
Marker	C8, F26, F28, T9, T10, T13, T16, T18	HOLD, UNCAP, RECAP, WRITE
Marker cap	C16, T17, T53	HOLD, UNCAP, RECAP
Kit	C6, C7, C8, C11, F28, T22, T35	HOLD, OPEN
Kit tab	T21	HOLD, OPEN
Canister	C1, C6, C8, T2, T18, T26, T57	HOLD, INSERT, REMOVE
Tube	C2, C6, C7, C8, F17, F26, T4, T17, T23, T24, T27, T28, T29, T30, T70	HOLD, INSERT
Needle	C8, T21, T28, T33, T60	UNCAP, HOLD, PIERCE, UNPIERCE
Needle cap	C14, T4, T28	UNCAP
Rinse glass	C6, C12, T2, T18, T34, T35, T38, T39, T51, T58, T69	HOLD
Red plug	F26, T21	HOLD, INSERT, REMOVE
Glass vial	T45	HOLD, OPEN
Yellow plug	T21	HOLD, INSERT
Tube clamp	C16, T28, T65	HOLD, CLAMP, UNCLAMP
Scissors	C8, C16, T68, T68_	HOLD, CUT
Number of pairs (objects, grasp types)		81

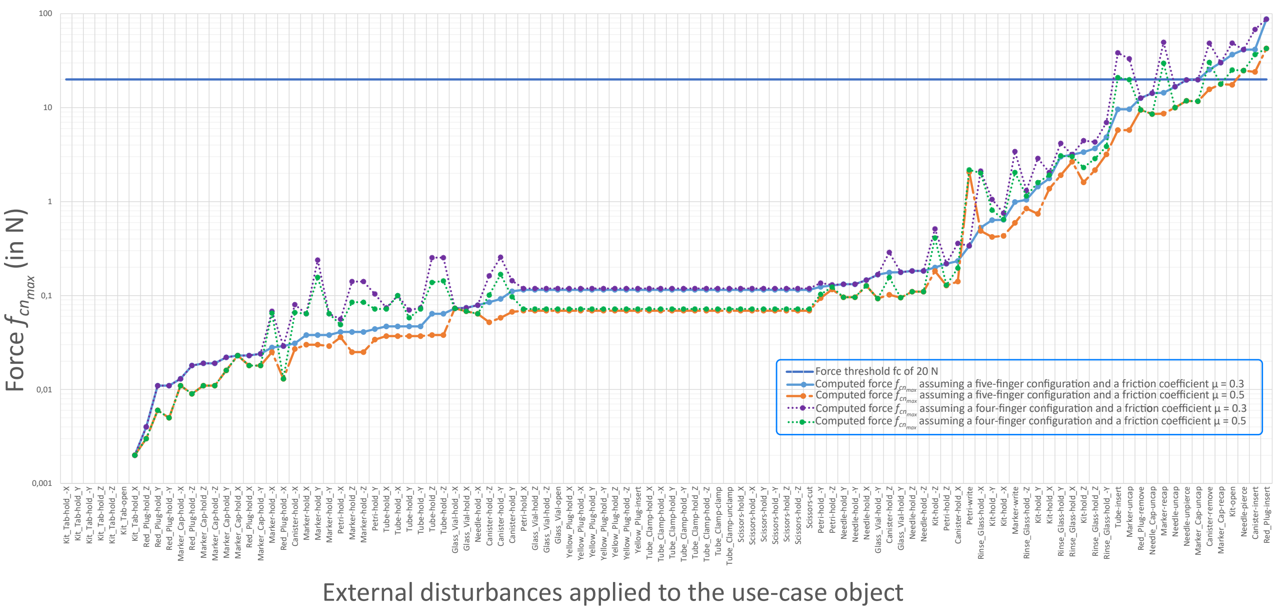

Figure 6. Theoretical required level of force to be applied at contact points of all objects as a function of external disturbances (computed forces assuming a pessimistic $\mu = 0.3$ and optimistic $\mu = 0.5$ friction coefficient in the HF contact modeling) for a five-finger and four-finger multi-fingered gripper configuration.

minimum required tightening force to be applied at contact points when holding the current object in order to perform the task (i.e. withstand the external disturbances applied on it) gives preliminary insights on the required grasping force. These calculations were carried out in two cases: the first by considering all contact surfaces involved in the grasp patterns using all five fingers, and the second one by removing the contact surfaces produced by the little finger. The latter corresponds to a simplified four fingers configuration which is a priori easier to manufacture, lighter, and more compact. Our goal is to see whether this simplification leads to a rise in the required grasping forces which would require larger actuators and cancel its theoretical advantages. Figure. 6 presents the comparison of the required force values to perform the tasks of the use-case using five-finger and four-finger configurations with friction coefficients of $\mu = 0.3$ and $\mu = 0.5$.

Comparing the required levels of effort between them highlights several interesting results.

1) Realizing the tasks of the sterility testing process requires a wide range of effort levels from a few mN up to 80N.
2) The majority of tasks (93% and 90% for a five-finger and four-finger configuration, respectively) require moderate efforts (less than 20N).
3) A 20N force threshold can be considered as a realistic upper bound for the physically reachable force to be produced by a robotic gripper.
4) The tasks that require the highest levels of effort deal with specific use-case related operations that involve direction-dependent external disturbances (such as INSERT, PIERCE, etc.) that could be produced by the robot arm carrying the gripper, provided the grasped object is for example pushed using the palm.

IV. Discussion about technical specifications and recommendations for a future gripper design

Having presented in detail our methodology and its application to the study of the manual gestures encountered in the sterility-testing process, we have concluded the following regarding a robotic multi-fingered gripper that would be well suited for the reproduction of the associated tasks:

1) From the human-centered gesture analysis:

- A four-finger configuration will be sufficient to carry out the described use-case process.
- Each finger should have three DoFs including flexion-extension.
- Tactile sensors should be incorporated in the three phalanges of each finger and the area of the palm near the proximal phalanx of each finger. The surfaces of the distal phalanges have the highest priority in the placement of tactile sensors, then the intermediate phalanges, the proximal phalanges, and finally the palm.
- It is highly recommended to integrate tactile sensors on the side of the intermediate phalanx of one finger.
- Finger dimensions can be set between 1 and 1.5 times the average size of the human index finger. Under this reasoning, a palm size of approximately 10 cm in diameter is sufficient to manipulate all the objects in the use-case.
- The contact surfaces of the gripper should be covered with a material that provides sufficient adherence to objects and is thin enough to minimally interfere with the readings of the tactile sensors.

2) From the force-based grasp stability analysis:

- In order to successfully perform 90% of the tasks described above, the actuation system of each finger should provide 20N at the finger tip. This means that the combination of electromechanical elements (electric motors, pulleys, cables, gears, etc.) must be optimized in order to generate the solicited amount of effort. In the case of electric motors, these can be brushless DC motors to facilitate their regulation in the control scheme.
- To perform the tasks that require more than 20N, we suggest as a future work proposing non-human-based grasps, which may contain more contact points or a redistribution of them to reduce the required amount of effort. Then by using the previously described grasp-quality metric, verify to which extent the required efforts are reduced.

V. Conclusions

The objective of this paper was to introduce a novel design methodology to provide technical specifications, as well as recommendations for the design of multi-fingered grippers focused on a specific process. The described methodology merges two types of analyses, one centered on the analysis of the human hand gestures and grasps used while performing some task (Human-centered gesture analysis), and the second focused on the forces exerted on the object (Force-based grasp stability analysis). As an example, it was applied to establish specifications for the design of a future multi-fingered robotic gripper that will perform the tasks that are involved in a sterility testing process. The first part of the methodology helped us to define the structural synthesis of the gripper, whereas the second part had the purpose of knowing the amount of effort that the future gripper must provide to perform each task of the use-case process to be automated.

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