Digital Handwriting with a Finger or a Stylus: a Biomechanical Comparison

Domenico Prattichizzo, *Senior Member, IEEE,* Leonardo Meli, *Student Member, IEEE,*
and Monica Malvezzi, *Member, IEEE*

Abstract—In this paper we present a study concerning the human hand during digital handwriting on a tablet. Two different cases are considered: writing with the finger, and writing with the stylus. We chose an approach based on the biomechanics of the human hand to compare the two different input methods. Performance is evaluated using metrics originally introduced and developed in robotics, such as the manipulability indexes. Analytical results assess that writing with the finger is more suitable for performing large, but not very accurate motions, while writing with the stylus leads to a higher precision and more isotropic motion performance. We then carried out two experiments of digital handwriting to support the approach and contextualize the results.

Index Terms—H.5.2 User Interfaces: Evaluation/methodology; H.5.2 User Interfaces: Input devices and strategies; handwriting; tablet; biomechanics; kinematics; hand model; stylus; touch.

✦

1 INTRODUCTION

The hand is the main tool adopted by humans to physically interact with the external environment. The human hand is highly versatile and easily adaptable to a variety of manipulation tasks, exposing flexible solutions to the needs of control [1]. In daily life, humans beings are, apparently without effort, able to generate complex and elegant movements of the hand and fingers, such as typing on keyboards, playing a musical instrument, or writing.

In this paper we focus on the analysis of human hand movements during handwriting tasks, a subject which has been studied for many decades.

In 1918 M. Freeman published a book [2] about the factors affecting performance in handwriting, using the so–called motion pictures of the act of handwriting. The role of hand biomechanical parameters in the handwriting process has been introduced by Schomaker and Plamondon in [3], in which they investigated the correlation between the force exerted with the pen and different kinematic parameters. In [4] a handwriting trajectory generation model, based on kinematics and dynamic optimization, was formulated and tested.

Hermsdörfer *et al.* [5] exploited information on the forces applied by the fingers on a pen, and the rela-
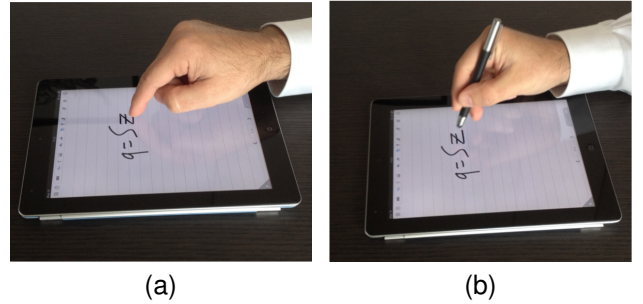

(a)   (b)

Fig. 1. The benchmark: writing on a tablet with the finger and with the stylus. Which solution is better?

tive grip kinetics, to inform diagnosis and treatment of handwriting disorders. In [6] a device called the Kinetic Pen was presented. It is capable of measuring the six-component force and torque that each of the individual contacts applies to the pen while writing. Shim *et al.* [7] adopted this device to investigate synergistic actions of hand-pen contact forces during circle drawing tasks. Kushki *et al.* [8] analyzed how some handwriting kinetic and kinematic parameters vary during a prolonged writing task, in children with and without handwriting deficiency. Falk *et al.* [9] developed an instrumented writing tool to measure kinematic and temporal information during a writing task, as well as forces exerted on the writing surface and on the barrel of the pen. They used this experimental setup to quantitatively measure the grip force variability, looking for a correlation with handwriting legibility, form, and strokes. In all these studies an important role is played by the main biomechanical properties of the hand, and by the grip force between the hand and the pen. This motivates the analysis approach proposed in this paper.

Due to the rapid development and diffusion of smart-

- D. Prattichizzo, L. Meli, and M. Malvezzi are with the Department of Information Engineering and Mathematics, University of Siena, Via Roma 56, 53100 Siena, Italy.

- D. Prattichizzo, and L. Meli are also with the Department of Advanced Robotics, Istituto Italiano di Tecnologia, via Morego 30, 16163 Genova, Italy.

phones and tablets, the handwriting problem, and in particular the interaction with the touchscreen through the finger or the stylus, is becoming more and more important (see Fig. 1) [10]. The direct use of the finger is more practical and typically allows one to save time, especially for short–term interactions, e.g., verifying a meeting time, navigating a map, answering a call, or controlling a media player. On the other hand, stylus–based input tools allow one to perform more complex operations and operate with smaller targets. In general, the finger interaction is less accurate than the stylus one [11].

One of the issues in writing with the finger is the ambiguous selection point created on the surface by the finger's contact area, together with the occlusion of the target [12]. Although there are several algorithms applied in gesture/finger detection allowing one to obtain a stable center with purely continuous movement, the lack of visual feedback can only be overcome with practice.

Using a stylus mitigates such problems: the contact patch is typically smaller and the vertical offset between the user's hand and the screen reduces occlusion issues. The selection points and the target trajectory can then be defined more clearly.

As a particular combination of the two interaction methods, a bimanual graphical editor application was presented in [13]. The cooperation between touch and pen interaction was also the basic idea of the interactive platform developed in [14].

One of the problems in the assessment of handwriting is the availability of objective indexes to evaluate handwriting performance. In [15] the problem of defining a handwriting legibility index was investigated. In particular, an experiment was performed on texts produced by children. The subjective rating of handwriting legibility, evaluated by some teachers, was related to an objective assessment based on a check list including 20 items.

In this work we contribute to the studies on handwriting presenting for the first time, at the best of our knowledge, a methodological approach based on the biomechanics of the human hand to compare two different input methods, i.e., the finger and the stylus, in digital handwriting tasks. Our analysis differs from other research presented in the literature. For instance, in the work by Zabramski [16], the author compares the accuracy and efficiency of different input methods in a line-tracing task without taking into account the human hand structure and kinematics. Although data-driven approaches are still crucial to address this type of problem, we believe that the kinematic of the hand can improve the comprehension of digital handwriting.

Some studies in the literature investigate the human–robot analogy in dexterity tasks, such as handwriting. In [17] the motion analysis of a redundant anthropomorphic arm was investigated during a writing task. In [18] the authors focused on the human–machine analogy in handwriting, including an evaluation of legibility.

In [19] the human–robot analogy was further investigated. A mathematical model of fatigue progress and an algorithm for human–like redundancy resolution were presented.

In this paper we present the analysis of handwriting on a touchscreen with numerical and analytic tools widespread in robotics; in particular we investigate manipulability properties. Generally speaking, a manipulability index is a number expressing the ratio between a measure of performance, e.g., displacement, velocity, force in the task space, and a measure of effort in the input/joint space [20], [21]. The manipulability analysis mainly consists in defining the directions in the task space, where the index is maximized or minimized. In this paper performance of two input methods in digital handwriting, i.e., finger and stylus, is evaluated and compared in terms of manipulability indexes in the task space [22], [23].

Beside the mathematical analysis based on a biomechanical model of the hand, two experiments are presented, in which subjects were asked to write on a touchscreen using either their index finger, or a stylus. The first experiment introduces the problem we modeled in this manuscript: some participants were asked to write a short sentence on a tablet and, for each sample, we measured the writing bounding box size, the path length, and the wrist motion. In the second experiment digital handwriting task performance was evaluated in terms of completion time and accuracy in retracing a given shape.

The paper is organized as follows: Section 2 introduces the problem presenting an experiment in which a handwriting task is performed on a tablet. Section 3 describes the kinematic model of the human hand, the joints, and the link geometries and parameters. Section 4 summarizes the main mathematical relationships necessary to evaluate hand performance, and specifically Section 4.4 covers the manipulability indexes. Section 5 presents the numerical simulations carried out to analyze the hand parameters during handwriting tasks. In Section 6 another experiment is explained and commented, in which subjects were asked to retrace a given shape on a touchscreen. Finally, Section 7 addresses concluding remarks.

2 EXPERIMENT: FREE HANDWRITING

In order to introduce the problem, we present the first experiment in which participants were asked to write a short sentence on a tablet using both the fingertip and a stylus. Fig. 2 shows the experimental setup, composed of an iPad (Apple Inc., Cupertino, California) tablet with a screen of 9.7″ diagonal and a resolution of 1024 by 768 pixels, a Bamboo Stylus (when required), and a simple framework that holds a camera at a distance of 35 cm above the tablet screen.

The camera, connected through a USB cable to a laptop with a specific program running, was able to track the
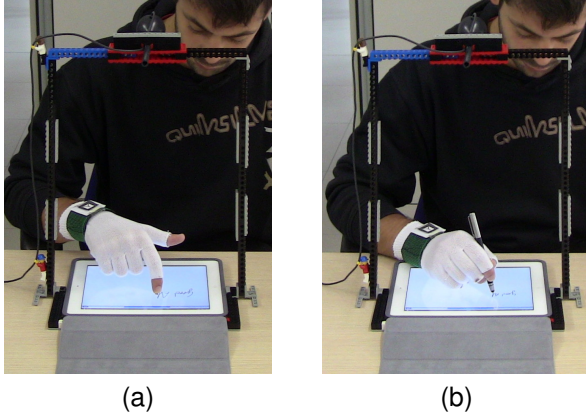
(a)   (b)

Fig. 2. Free handwriting experimental setup. The subject wears a non-conductive glove on the writing hand and a bracelet with a fiducial marker glued on the wrist. The glove does not cover the subject's fingertips. A camera is employed to track the the wrist during the task. The two tasks consisted in writing the words "Good afternoon" on a tablet screen with (a) the index fingertip, and (b) a stylus. Fourteen subjects participated to the experiment.
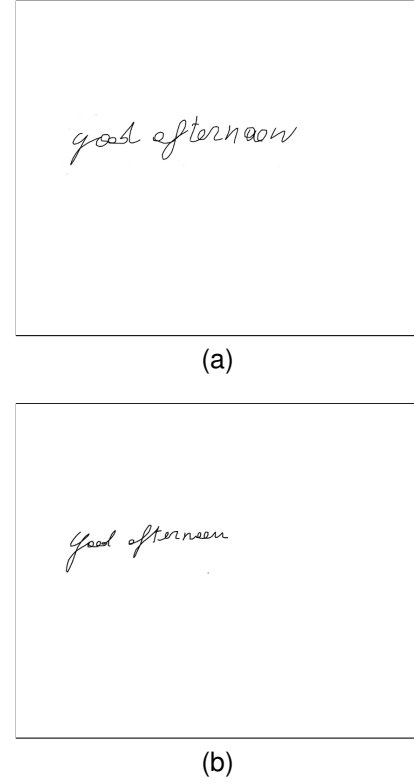

(a)

(b)

Fig. 3. Tablet screenshots of the handwriting experiment with a representative subject using (a) the index fingertip (task F), and (b) a stylus (task S). In this specific example the minimum bounding boxes enclosing the two words measured 54768 pixels when the fingertip was used and 37664 pixels when the stylus was used. Similarly the path length was 514 mm for task F, and 312 mm for task S.

motions in the 3D space of a 2x2 cm^2 fiducial marker. The tracker was based on the ARToolKit libraries [24], developed for building Augmented Reality applications. Having performed a careful two–step calibration we were able to achieve a zero–point failure in tracking the marker position of the order of 5 mm (on the plane parallel to the tablet surface).

Subjects wore a non-conductive glove on the writing hand, together with a bracelet with the fiducial marker. The glove was employed to isolate the part of the hand not used in the writing task, to avoid registering undesired contacts with the tablet's capacitive touchscreen. The glove did not cover the operator's fingertips, to guarantee a good grip with the stylus, and to allow the use of the index finger to write.

Fourteen volunteers, eleven males and three females, age range $20 - 35$ years, took part in the experiment. All of them were right–handed and had prior experience using a stylus, and doing finger operations on touchscreen devices. The participants were asked to write the words *Good afternoon* in cursive using the index fingertip (task F), and the provided stylus (task S) in the most natural way. Stylus and finger inputs were proposed to subjects in a randomized order. The marker, whose position was tracked through the camera, was placed on the subject's arm, such that the marker displacement could be referred as the participant's wrist motion. Only the displacement on the plane parallel to the tablet screen was considered in the experiment. In Fig. 3 screenshots of the tablet are reported for both finger and stylus inputs. On the top the index fingertip has been used (task F), while on the bottom the subject used the stylus to perform the handwriting task (task S). Note that the size of the words is very different between the two cases,

even though subjects were asked to write as naturally as possible without any constraint in size. The examples shown in the figure concern one representative subject, but similar behaviors were faced with all participants. Such a diversity may therefore be attributed to the tool used during the task.

2.1 Experimental results and discussion

To evaluate the performance of the tested handwriting methods (task F and task S) we computed (1) the length of the trajectory followed by the wrist during the handwriting action (wrist displacement), (2) the minimum bounding box and (3) the total path length of the written words. With total path length we refer to the length of the handwriting pattern written down on the tablet screen throughout the proposed writing task.

Data resulting from five couples of words (*Good afternoon*), relative to the same writing method and performed by the same subject, were averaged and then compared with the other task's data. Fig. 4a reports the total subject's wrist displacement, while Fig. 4b shows the minimum bounding box enclosing the two words for each task proposed. Finally, Fig. 4c depicts the path
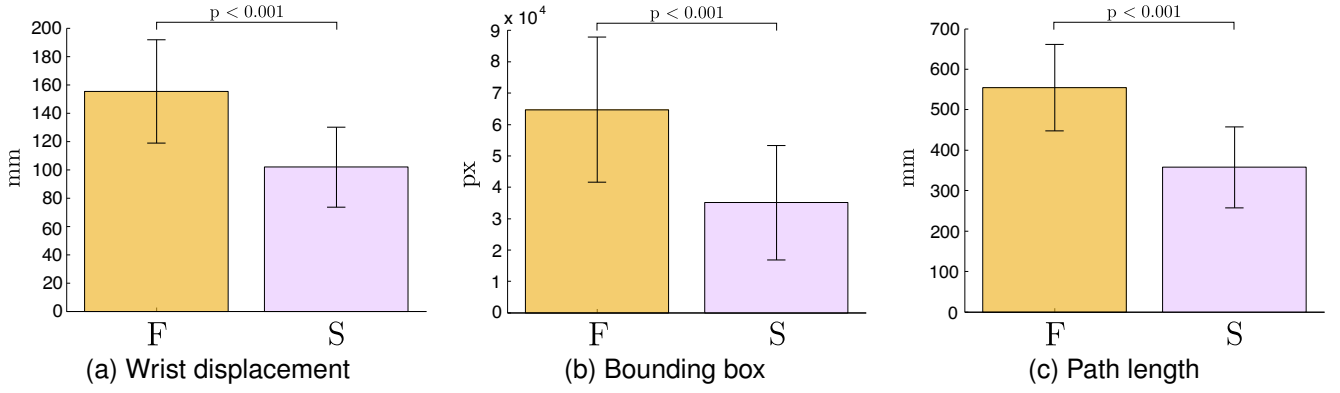
Fig. 4. Handwriting experiment. Wrist displacement, bounding box area, and path length (mean and SD are plotted) for the two writing methods, index fingertip (F), and stylus (S). Lower values of these metrics indicate higher performance in terms of ease of writing. The p-value of a paired t-test reveals a statistically significant difference between the writing techniques reported in each plot.

length written down on the screen. All data were averaged over all the subjects.

Means were then tested using a paired t–test and comparisons revealed significant differences among the two techniques tested in our experiment regardless of the metric considered. Details on the statistical analysis are reported in Table 1. Both bounding box and path length data have been transformed using the logarithm function in order to pass the Shapiro-Wilk normality test. No data transformation was required for the wrist displacement, since its distribution was already "approximately" normally distributed, i.e., paired t-test is quite "robust" to violations of normality, meaning that the assumption can be a little violated and the test still provides valid results.

The measure of wrist motion among the different proposed techniques is related to the energy expenditure during a writing task [25]. The gap in the wrist displacement between the two input methods is evident in Fig. 4a. Results show that writing with the fingertip induces a higher effort for the subject. Moreover, some participants stated that the writing position with the fingertip was less natural and comfortable, since the hand was completely suspended, rather than resting on the screen as in the case of the stylus writing.

The results of this test can be used to preliminarily and qualitatively assess the legibility issue, even though it is a matter of future investigations. Fig. 5 shows a comparison between one of the tasks performed with the fingertip and one performed with the stylus (randomly selected). Four subjects only have been included in the figure for the sake of space. The size of the written sentences was scaled in order to have the same width. From a qualitative point of view, there is no significant difference between the two tasks. It seems that people, based on the means used, seek to optimize legibility by varying word size.

This first experiment showed that measurable differences exist between the two digital writing methods analyzed in the experiment. In the following Section

Metric	Correlation	df	t value	p value
Wrist displacement	0.577	13	6.522	< 0.001
Bounding box area	0.603	13	6.108	< 0.001
Path length	0.551	13	7.175	< 0.001

TABLE 1
Paired samples t-test results. Comparisons are between data about the finger (F) and the stylus (S) tasks. The confidence interval is 95%.

Fig. 5. Handwriting quality comparison. Two representative cases are shown for four representative subjects, when the index fingertip (on the left), and the stylus (on the right), were used to write. Words are scaled so that they all have the same width.

we will attempt to correlate such differences with the biomechanical and kinematic properties of the human hand.
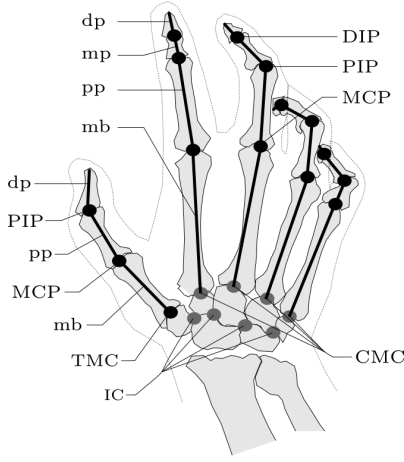
Fig. 6. Bones and joints of the human hand.
mb is metacarpal bone, *pp* is proximal phalanx, *mp* is middle phalanx, *dp* is distal phalanx, *TMC* is trapeziometacarpal joint, *CMC* is carpometacarpal joint, *MCP* is metacarpophalangeal joint, *PIP* is proximal interphalangeal joint, *DIP* is distal interphalangeal joint, and *IC* is intercarpal joint. Joints represented with grey dots are not included in our model.

Finger	mp/dp	pp/dp	mb/dp	dp
Thumb	–	1.37	2.09	22
Index	1.41	2.45	4.17	19
Middle	1.60	2.54	3.71	21
Ring	1.50	2.33	3.25	20
Little	1.15	2.04	3.32	17

TABLE 2
Table of bone-to-bone length ratios for the right hand and lengths of the distal phalanx bones (mm).

3 MODELING THE HUMAN HAND

In this work we consider a 20-DoF hand kinematic model to analyze different aspects of human hand grasping [26], [27], [28]. Its main features are here summarized.

The skeleton of the human hand consists of 27 bones: 8 short bones constitute the wrist, or carpus, which articulate with the forearm and the proximal parts of the 5 metacarpal bones. These bones form the palm and, together with the 14 phalanges (proximal, medial, and distal), compose five serial kinematic chains, i.e., the fingers. Fig. 6 shows the structure of the human hand skeleton. The hand size, and in particular the length of the bones, is specific to each person and varies with age. However the ratios between the length of each finger are typically considered constant [29], [30]. Table 2 shows the length ratios of the hand bones w.r.t. the length of the distal phalanx of each finger [30], and, in the last column, the length of the distal phalanges considered in this work to model the hand. The index, middle, ring and little fingers are generally represented with the same kinematic structure, in terms of joints

number and arrangement. The proximal and distal interphalangeal articulations (PIP, DIP) can be represented as a one-DoF revolute joint. The metacarpophalangeal (MCP) articulations, connecting fingers to the palm, are usually represented as a two-DoF joint, consisting of two revolute joints with an orthogonal axis. The first rotation describes the adduction/abduction motion, while the other one describes the finger flexion/extension.

In our simplified model we assumed that MCP flexion/extension, PIP and DIP joints have parallel rotation axes, even though anatomical studies and experimental measures showed that their rotation axes are slightly inclined [31]. Furthermore, some biomechanical models, e.g., those described in [32], also include the modeling of the intercarpal articulations (IC). Since the rotation range of such articulations is small with respect to the others, they have not been considered in this work.

The human ability of grasping and manipulating objects strongly depends on thumb kinematics and on its capability of opposing the other fingers. The carpometacarpal (CMC) joint articulates the distal row of carpal bones and the proximal bases of the five metacarpal bones. The CMC of the thumb is also known as the trapeziometacarpal joint (TMC), and significantly differs from the other four CMCs. The TMC is the most important joint to define thumb kinematics. Analyzing the anatomical bone shape, we should model it as a complex saddle joint, however, in the literature, the TMC is often approximated with a two-DoF joint with orthogonal axes [26], [32], [33].

The MCP should also be modeled as a two-DoF joint, nevertheless, since the adduction/abduction motion range is small, it can be neglected and the MCP can be modeled as a one-DoF revolute joint. The interphalangeal articulations, PIP and DIP joints, are represented as a one-DoF revolute joint. In Fig. 6 all the articulations' names and positions are reported.

Table 3 shows the Denavit–Hartenberg parameters of the thumb and index fingers. The middle, ring and little parameters can be similarly defined by the values of the index.

4 MODELLING THE HANDWRITING TASK

4.1 Main definitions

Let us indicate with $\{N\}$ a reference frame fixed to the palm of the hand, whose origin is in the wrist rotation center [34], and with $q \in \Re^{n_q}$ a vector containing the hand joint angles. According to the hand kinematic model described in the preceding section, $n_q = 20$.

In this paper we compare two possible ways to perform a digital handwriting task. In the first case the index finger is directly used to write, while in the second case a stylus is employed.

Studying the writing task, we consider only the translational components of the end–effector six–dimensional displacement, while the end–effector rotations are disregarded. Let us indicate with $u \in \Re^3$ the translational

Thumb					
Joint	id.	a_j	α_j	d_j	θ_j
TMC	1	0	$\pi/2$	0	θ_1
TMC	2	$a_{t,2}$	$\pi/2$	0	θ_2
MCP	3	$a_{t,3}$	0	0	θ_3
PIP	4	$a_{t,4}$	0	0	θ_4
Index					
Joint	id.	a_j	α_j	d_j	θ_j
MCP	1	0	$-\pi/2$	0	θ_5
MCP	2	$a_{i,2}$	0	0	θ_6
PIP	3	$a_{i,3}$	0	0	θ_7
DIP	4	$a_{i,4}$	0	0	θ_8

TABLE 3
Denavit Hartenberg parameters for thumb and index
fingers.

Fig. 7. Kinematic scheme and main parameters of the human hand interacting with the environment through the index fingertip.

displacement of the end–effector, namely the index finger in the first case and the stylus tip in the second one. We furthermore indicate with w the wrench exchanged during the interaction with the surface of the screen, i.e., the writing surface. By assuming a single point with friction to model the contact with the screen [35], the torque components of the wrench w are null, so we can consider $w \in \Re^3$. The kinematic model used in this paper relates the end–effector displacement to hand joint angle variations, while the kinetostatic model relates the force applied to the end–effector and the joint torques collected in vector $\tau \in \Re^{n_q}$. However, human hand joints are actuated by a quite complex and coupled neuromuscular system [36]. Joint torques are related to muscle forces by the following relationship

$$\tau = f_m(F_m),$$

in which $F_m \in \Re^{n_m}$ represents the muscle force vector, and $f_m : \Re^{n_m} \to \Re^{n_q}$ is a function modeling the muscolar–tendinous system. In [37] the authors showed that such a function is nonlinear, it depends on hand configuration and it was evaluated as a function of the moment arm of each tendon and of the muscles' physiological cross–sectional area [38]. In this paper, since we mainly focus on hand skeleton kinematic structure, we do not consider the transmission between joint torques and muscle forces.

4.2 Writing with the finger

In this section we model digital handwriting with the index finger as shown in Fig. 7. Let $\{B_{in}\}$ be the index finger reference system, whose origin O_{in} is in the intersection between the two revolute joint axes which define the MCP articulation. The position and orientation of $\{B_{in}\}$ frame w.r.t. $\{N\}$ is described by the homogeneous transformation matrix T_{in}. Let $q_{in} \in \Re^4$ be a vector containing the joint angles relative to the index finger.

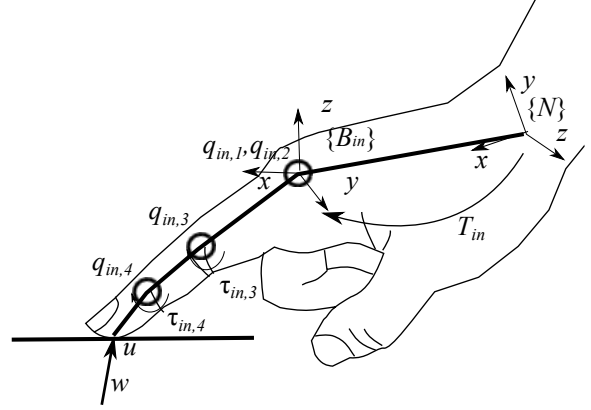The index fingertip velocity $\dot{u}$ is related to the time derivative of the index joint angular velocities $\dot{q}_{in}$ by the equation

$$\dot{u} = J_{in}\dot{q}_{in},$$

where $J_{in} \in \Re^{3 \times 4}$ is the index finger Jacobian matrix [35]. This relationship can be expressed in terms of displacement variation as

$$\Delta u = J_{in}\Delta q_{in}, \tag{1}$$

where Δu represents the displacement of the index finger. Such an expression represents the linearization of the standard forward kinematics relationship and it is valid for small displacements only. In addition, the relationship between the force w, that the fingertip applies to the writing surface, and the torques $\tau_{in} \in \Re^4$ applied at the finger joints is

$$\tau_{in} = J_{in}^{\mathrm{T}}w.$$

4.3 Writing with a stylus

When the hand writes with a stylus, two aspects should be considered: (1) the grasping of the stylus, and (2) the interaction between the stylus and the writing surface.

There are different ways to shape and position the hand and the stylus during handwriting tasks [39]. In this paper we assume the most common configuration, in which the stylus is in contact with the hand in four areas: the thumb and index finger, the medial surface of the middle finger distal phalanx, and the part of the hand located between the thumb and the index MCPs, as shown in Fig. 8.

At each contact area, a contact wrench is applied to the stylus by the fingers, or the hand. Due to finger compliance, the contact is extended on an area whose dimension depends on the skin deformation properties and on the contact force [40]. For the sake of simplicity, in this work we represent a contact as a point, and the
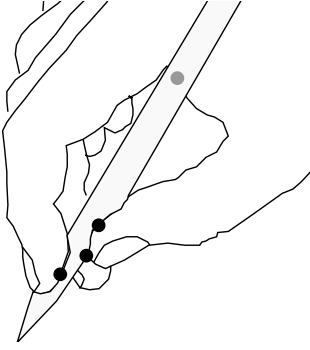
Fig. 8. The stylus is in contact with the hand in four areas: the thumb and index fingers, the medial surface of the middle finger distal phalanx, and the part of the hand located between the thumb and the index MCPs. The black contact points are modeled as single point with friction (hard finger) model. The gray point is not considered in the analysis.

contact force applied on it is the result of the stress distribution arising in the contact patch, due to the skin deformation. A single point with friction contact model is adopted to model the contact between the stylus and the fingers [35]: at each contact point, the contact wrench is composed of a three dimensional force without torque, in which the force components, normal and tangential to the contact surface, satisfy the Coulomb friction constraint.

Generally during writing tasks the three contact points with the fingers do not significantly change in the stylus reference system, while the contact point on the palm may vary, due to the sliding between the stylus and the skin. Since the force at the contact point on the palm is typically much lower than the others, and the sliding contact with the palm's surface does not significantly affect stylus motions, the contact point on the palm can be neglected. We assume that this approximation does not significantly affect the results in terms of kinematics performance, while it could have a role in the force distribution. Considering that in the numerical simulation presented in this paper we focus mainly on kinematic analysis, we do not consider this point in this preliminary work. The role of the palm's contact point, as well as the dependency with respect to hand posture and the hand's physical characteristics, will be considered in future developments of this study. We furthermore assume that the surface on which the hand is writing is fixed. The location of the contact points is qualitatively represented in Fig. 8, with the neglected point on the palm drawn in gray. Let us collect in the vector $c^h \in \Re^9$ the configuration of the three contact points on the hand, with respect to the wrist reference frame $\{N\}$. A small variation of the contact point configuration can be approximately expressed as a linear function of the hand joint variables as

$$\Delta c^h = J \Delta q,$$

where $J \in \Re^{9 \times 20}$ is the hand Jacobian matrix, which can be evaluated using standard robotic analysis tools [35], [41], [42]. The transpose of the hand Jacobian matrix makes it possible to describe the relationship between the forces applied on the contact points and the joint torques as

$$\tau = J^{\mathrm{T}} \lambda,$$

where $\tau \in \Re^{20}$ indicates the joint torque vector, and $\lambda \in \Re^9$ is the contact force vector. Referring to Fig. 9, let us indicate with $\{B\}$ a frame on the stylus tip, whose position w.r.t. the hand reference frame $\{N\}$ is defined by the vector $u \in \Re^3$. Consider $c^o \in \Re^9$ a vector containing the coordinates of the contact points on the object. Note that $c^o \neq c^h$ due to contact compliance model. A variation of the object contact point configuration can be evaluated as a function of the object frame displacement, as

$$\Delta c^o = G^{\mathrm{T}} \Delta u,$$

where $G^{\mathrm{T}} \in \Re^{9 \times 3}$ is the transpose of the grasp matrix [35], [42]. The grasp matrix furthermore models the relationship between the force $w \in \Re^3$ applied to the stylus tip, due to the interaction with the writing surface, and the contact forces λ as

$$w = -G\lambda.$$

Fingertip compliance is represented by the following equation

$$\lambda = K_c \left(\Delta c^h - \Delta c^o \right),$$

where $K_c \in \Re^{9 \times 9}$ is the contact stiffness matrix, symmetric and positive definite, whose elements depend on fingertip compliance properties [40]. The relationships introduced above can be linearized and organized in a linear homogeneous system as

$$\begin{bmatrix} I & G & 0 & 0 & 0 \\ 0 & -J^{\mathrm{T}} & I & 0 & 0 \\ 0 & I & 0 & K_c G^{\mathrm{T}} & -K_c J \end{bmatrix} \begin{bmatrix} \Delta w \\ \Delta \lambda \\ \Delta \tau \\ \Delta u \\ \Delta q \end{bmatrix} = 0. \quad (2)$$

Its solution describes how the system, composed of the hand and the stylus, can evolve starting from an initial reference equilibrium configuration, and can be written as

$$\Delta x = \Gamma \xi,$$

where Δx is the unknown vector, defined as

$$\Delta x = \begin{bmatrix} \Delta w^{\mathrm{T}} & \Delta \lambda^{\mathrm{T}} & \Delta \tau^{\mathrm{T}} & \Delta u^{\mathrm{T}} & \Delta q^{\mathrm{T}} \end{bmatrix}^{\mathrm{T}},$$

Γ is a matrix whose columns form a basis of the null space of the linear system coefficient matrix, and ξ is a vector of coefficients that parametrizes the solution. Further details can be found in [43]. In the specific grasp configuration considered in handwriting with the
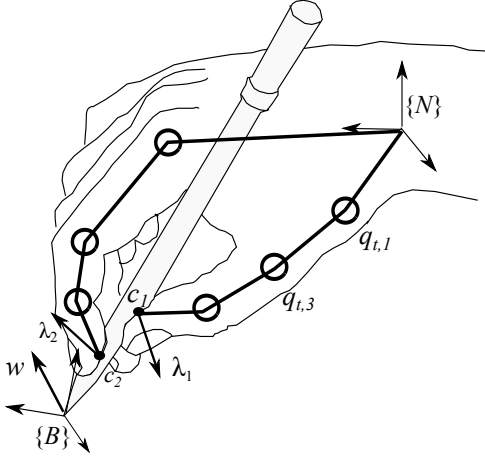
Fig. 9. Hand holding a stylus. Hand and stylus frames, external wrench and contact points on the thumb and index fingers with corresponding contact forces. For the sake of simplicity the contact point on the middle finger is not displayed.

stylus, the coefficient matrix of eq. (2) belongs to $\Re^{32 \times 55}$, the unknown vector $\Delta x \in \Re^{55}$, and consequently the solution matrix, a basis of the null space, is $\Gamma \in \Re^{55 \times 23}$. The vector $\xi \in \Re^{23}$ can be furthermore organized as

$$\xi = \begin{bmatrix} \xi_c^{\mathrm{T}} & \xi_h^{\mathrm{T}} & \xi_{rb}^{\mathrm{T}} & \xi_r^{\mathrm{T}} \end{bmatrix}^{\mathrm{T}},$$

where $\xi_c \in \Re^6$ describes the coordinated hand/stylus motions compatible with eq. (2), involving both stylus force variation Δw and hand motion. $\xi_h \in \Re^3$ parametrizes the internal forces, i.e., contact force variations that do not involve changes in the force applied to the stylus tip. $\xi_{rb} \in \Re^3$ describes the stylus rigid body motions, i.e., hand and stylus motions that do not change contact forces, and $\xi_r \in \Re^{11}$ the hand joint redundant motions, i.e., hand joint motions that do not change contact forces and stylus tip displacement. According to this partition, matrix Γ can be written as follows

$$\Gamma = \begin{bmatrix} \Gamma_{w,c} & 0 & 0 & 0 \\ \Gamma_{\lambda,c} & \Gamma_{\lambda,h} & 0 & 0 \\ \Gamma_{\tau,c} & \Gamma_{\tau,h} & 0 & 0 \\ \Gamma_{u,c} & \Gamma_{u,h} & \Gamma_{u,rb} & 0 \\ \Gamma_{q,c} & \Gamma_{q,h} & \Gamma_{q,rb} & \Gamma_{q,r} \end{bmatrix}.$$

4.4 Manipulability analysis

In this work we evaluated handwriting performance in terms of manipulability. The purpose of manipulability indexes is to provide a quantitative measure of the ability to move and apply forces in arbitrary directions. Such indexes take into account the kinematics of the human hand when it carries out specific tasks, for instance in handwriting, and can be adopted as a measure to evaluate grasp and dexterity performance.

Manipulability indexes were initially introduced in [21], [22], and since that time they have been widely used in robotics analysis, task specification, and mechanism design. The manipulability concept mainly consists in describing directions in the task/joint space, which maximize/minimize the ratio between a measure of effort in joint space and a measure of performance in task space. If quadratic functions of the joint and task parameters are chosen as these measures, and the relationships between the two sets of variables are linear, then the manipulability analysis consists in solving an eigenvalue problem. Different manipulability indexes and measures have been proposed in the literature, since different physical parameters can be chosen to measure effort and performance. The most widely adopted is the kinematic manipulability index and in this paper, for the sake of brevity, we considered only that.

An uncertainty in the definition of the joint variation Δq may cause an error at the end–effector, i.e., the index fingertip or the stylus tip, configuration, that can be quantified as Δu.

Salisbury and Craig in [22] defined the kinematic manipulability index as

$$R_k = \frac{\Delta u^{\mathrm{T}} W_u \Delta u}{\Delta q^{\mathrm{T}} W_q \Delta q}, \tag{3}$$

where R_k can be interpreted as the ratio between the norm of errors in positioning the end–effector Δu, and the norm of errors Δq in controlling joint angles to their set–points. W_u and W_q are two symmetric and positive definite matrices, adopted to weigh each component of Δu and Δq in the evaluation of the performance index R_k. The kinematic manipulability index quantifies how joint tolerances and mechanical clearance affect the task precision: a lower R_k value means a lower amplification of joint uncertainties in the task space, corresponding to a higher precision of the task. The analysis of R_k can be straightforwardly performed, once a correspondence between the numerator and the denominator variables, namely Δu and Δq in eq. (3), is established.

When the index handwriting is considered, the end–effector displacement is simply the displacement of the fingertip, and, according to eq. (1), the kinematic manipulability index expression can be rewritten as

$$R_k = \frac{\Delta q_{in}^{\mathrm{T}} J_{in}^{\mathrm{T}} W_u J_{in} \Delta q_{in}}{\Delta q_{in}^{\mathrm{T}} W_q \Delta q_{in}}.$$

The manipulability analysis defines how an arbitrary variation of the input joint angles Δq is reflected in the end–effector displacement Δu. It is realistic to assume that the joint variation angles are bounded, therefore the end–effector displacement will be bounded as well. The norm of the bound may be chosen arbitrarily, since a linear relationship is established by eq. (1). The unit is typically chosen for the bounds, i.e., $\|\Delta q_{in}\| \le 1$, where $\|.\|$ indicates the Euclidean norm. We can then represent all the possible joint variations as a unit sphere in the n_q–dimensional space. This sphere, through the

matrix J_{in}, is mapped in the generalized end–effector coordinate space into an ellipsoid, which is called a kinematic manipulability ellipsoid. In particular, if we choose $W_u = I$ and $W_q = I$, the length of the ellipsoid semiaxes can be evaluated as the singular values of the matrix J_{in}, while the directions of the axes are evaluated as the eigenvectors associated to each singular value, respectively.

When the problem of writing with a stylus is taken into account, the one–to–one mapping between numerator and denominator of eq. (3) can be done considering the solution of the homogeneous system in eq. (2), as detailed in [44]. To consider the ratio in eq. (3) well–defined, a one–to–one mapping should be established between the task and the actuated joints. Unfortunately this type of mapping does not generally exist, because of the possible presence of kinematic redundancy and indeterminacy [35]. In [44] the complete problem solution is provided.

In this work, to evaluate the kinematic manipulability index, we considered only rigid body motions, i.e., co-ordinated hand and stylus motions that do not involve changes in the contact forces. According to the solution of the homogeneous system in eq. (2), stylus motion and hand joint variations can be evaluated in this case as

$$\Delta u = \Gamma_{u,rb}\xi_{rb},$$
$$\Delta q = \Gamma_{q,rb}\xi_{rb}.$$

Thus eq. (3) can be rewritten as

$$R_k = \frac{\xi_{rb}^{\mathrm{T}}\Gamma_{u,rb}^{\mathrm{T}}W_u\Gamma_{u,rb}\xi_{rb}}{\xi_{rb}^{\mathrm{T}}\Gamma_{q,rb}^{\mathrm{T}}W_q\Gamma_{q,rb}\xi_{rb}}.$$

The force manipulability index can be similarly defined as the ratio of a performance measure in the space of forces exchanged with the environment, and an effort measure in the space of actuated joint torques as

$$R_f = \frac{\Delta w^{\mathrm{T}}W_w\Delta w}{\Delta\tau^{\mathrm{T}}W_\tau\Delta\tau}.$$

Here, weights in W_τ and W_w incorporate different costs in generating joint torque, or forces, and may represent task specifications, i.e., greater relevance along certain directions. For instance, in human hand kinematic models the weight matrix can be used to deal with biomechanical factors, such as muscle strength and moment arm of the tendons [38].

In this paper, for the sake of brevity, we evaluated and analyzed the kinematic manipulability index only. However, in future developments of this research we will analyze the force manipulability as well, and, in particular, we will investigate its relationships with handwriting force and pressure.

5 NUMERICAL SIMULATIONS

To reproduce and analyze grasps with hands we performed a series of numerical simulations with *SynGrasp*
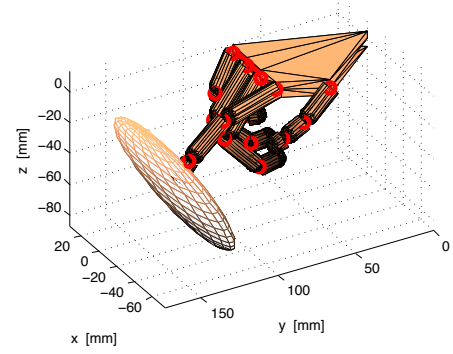

Fig. 10. Kinematic manipulability ellipsoid obtained considering the index fingertip as end–effector.

[45], a Matlab Toolbox for grasp analysis with human and robotic hands. SynGrasp includes functions to define the hand kinematic structure and the contact points with a grasped object. The coupling between joints induced by a synergistic control can be modeled if needed. The hand modeling tools make it possible to define compliance at the contact, at the joint, and at the actuator levels. Furthermore the analysis functions provided can be used to investigate the main grasp properties: controllable forces, object displacement, manipulability analysis, and grasp quality measures. Functions for the graphical representation of the hand, of the object, and of the main results analysis are also available. As a preliminary outcome of this study, the Matlab code developed to perform the numerical simulations described in this paper, specifically devoted to the digital handwriting evaluation problem, has been included as an application example in the SynGrasp Toolbox currently available in the toolbox website.[1]

As discussed in the preceding sections, in this study we neglect the compliance at the joint level and we consider contact stiffness only. The elements of the K_c matrix are defined according to data and results available in the literature. For the sake of simplicity, an isotropic model is considered, i.e., $K_c = k_c I$, with $k_c = 1000$ N/m [40].

In the numerical simulations presented in this section, we focus on the relationship between the performance in the workspace and in the hand joint space, and we do not consider the tendinous–muscular arrangement of hand and fingers. In the evaluation of kinematic manipulability indexes, we then assume the same weights for all the joints, i.e., $W_q = I$. In the workspace, all the displacement components are considered with the same weight as well, i.e., $W_u = I$.

5.1 Writing with the fingertip

Fig. 10 shows the kinematic manipulability ellipsoid obtained considering the index fingertip as end–effector.

1. SynGrasp can be downloaded from the following web page: http://sirslab.dii.unisi.it/syngrasp/
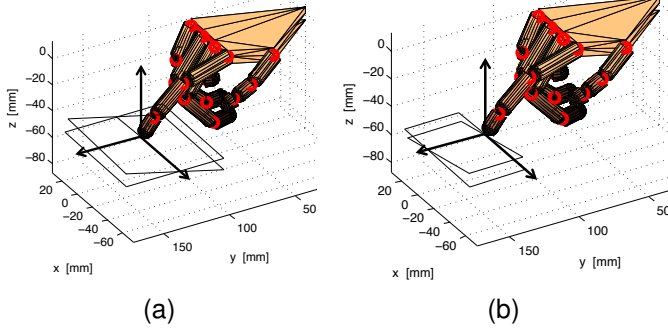
(a)   (b)

Fig. 11. How the writing plane orientation changes. (a) Rotation of the writing plane about the x axis, (b) rotation of the writing plane about the y axis.

(a) Rotation of the writing plane about the x axis

(b) Rotation of the writing plane about the y axis

Fig. 12.   Projections of the kinematic manipulability ellipsoids on the writing plane, when the index finger is used to write and different rotation angles of the writing plane are taken into account.

The principal ellipsoid axes orientation, w.r.t. the wrist reference frame, can be described by the rotation matrix

$$R = \begin{bmatrix} -0.5171 & 0.1098 & 0.8488 \\ -0.0571 & -0.9940 & 0.0938 \\ 0.8540 & -0.0000 & 0.5203 \end{bmatrix},$$

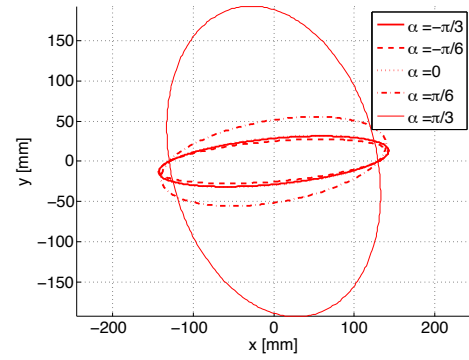and the ellipsoid semiaxes lengths are $a_1 = 92$ mm, $a_2 = 70$ mm, and $a_3 = 10$ mm.

In a handwriting problem, the end–effector substantially moves on a flat surface, i.e., the writing plane. The intersection between the manipulability ellipsoid and this plane is then evaluated, in order to understand performance in terms of kinematic manipulability of this specific task. As reference writing surface we assumed a plane passing through the index fingertip and parallel to the xy plane defined by the wrist reference frame, i.e., the transverse plane of the hand. We then analyzed how the ellipse, obtained from the intersection, varied as the writing plane was rotated about the x and y axes. We took into account rotations by an angle α between $-\pi/3$ and $\pi/3$ w.r.t. the x axis and by an angle β between $-\pi/3$ and $\pi/3$ w.r.t. the y axis, as shown in Fig. 11.

By observing the results in Fig. 12, we can note that the kinematic manipulability index computed for the index fingertip, and evaluated considering the writing plane as the task space, has a high variability w.r.t. the writing plane inclination. Both the shape and the size of the kinematic manipulability ellipse sensibly change when the plane is rotated about x and y axes. This sensitivity is particularly evident when the writing plane is rotated w.r.t. the x axis (Fig. 12a). The rotation w.r.t the y axis essentially produces only a rotation of the intersection ellipse (Fig. 12b).
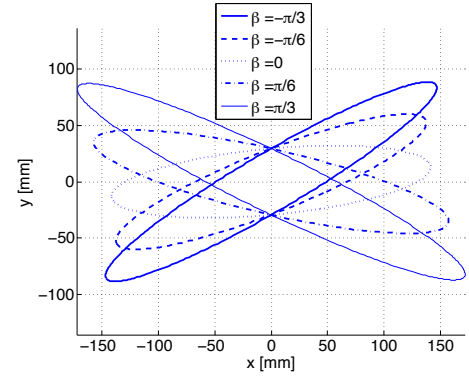
5.2 Writing with a stylus

The hand and the stylus reference configurations have been assumed from a series of preliminary experimental measures [39].

Since the goal of this paper is an analysis of a digital handwriting task and in particular a comparison between writing with a stylus and with the index fingertip,

we considered just one configuration for each case. The configurations considered represent an average case. In this paper we firstly presented and detailed the models and the methods we adopted to perform the study. For the sake of brevity we could not take into account several hand characteristics and configurations, even though we expect that they can affect handwriting performance. This aspect will surely be investigated in a future work.

In this case, the hand Jacobian J, the grasp matrix G, and the contact stiffness matrix K_c size were 9×20, 3×9, and 9×9 respectively. A single point with friction [35] was assumed to model the contact between the fingers and the stylus, and between the stylus and the writing plane.

We again performed the same manipulability analysis described for the fingertip writing problem in the preceding subsection. Fig. 13 shows the kinematic ellipsoid obtained considering the stylus tip as the reference point of the grasped object. The principal ellipsoid axes orientation w.r.t. the wrist reference frame could be defined
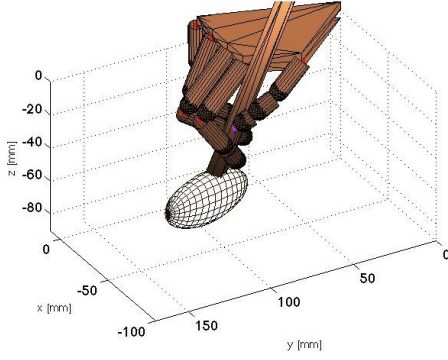
Fig. 13. Kinematic manipulability ellipsoid evaluated on the tip of the stylus.

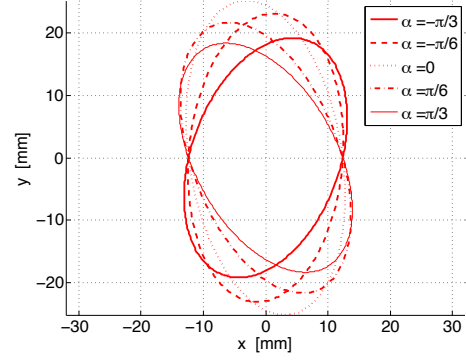this time by the following rotation matrix

$$R = \begin{bmatrix} -0.02 & 0.37 & -0.73 \\ 0.98 & -0.13 & -0.51 \\ 0.20 & 0.64 & 0.21 \end{bmatrix},$$

and the semiaxes lengths are $a_1 = 24.0$ mm, $a_2 = 18.08$ mm and $a_3 = 10.24$ mm. Observe that the direction along which the kinematic manipulability is larger, is approximately aligned with the y axis of the hand reference system (first column of the R matrix).
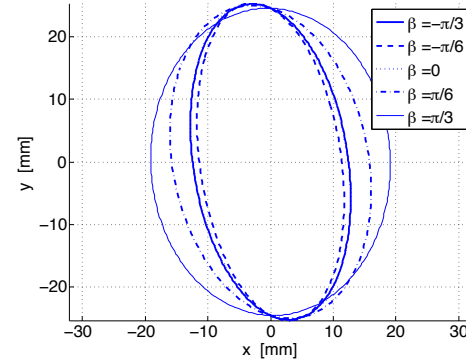
The sensitivity of the intersection between the kinematic manipulability ellipsoid and the writing plane was again analyzed for different writing plane orientations. The plane orientation range was the same described for the fingertip writing problem, i.e., rotations between $-\pi/3$ and $\pi/3$ both in the x and y directions are considered. Fig. 14 shows the variations of the kinematic manipulability ellipsoid projection on the writing plane for different orientations of the writing plane itself. Despite the fingertip case the resulting ellipse has a small sensitivity w.r.t. the writing plane orientation.

5.3 Discussion of the numerical results

Some considerations on human hand capabilities in digital handwriting tasks arise from the analysis of the obtained results. Firstly, comparing the sizes of the kinematic manipulability ellipsoids, observe that the one reached considering the fingertip as end–effector is much larger than the one obtained using the stylus. More in detail, the maximum ellipsoid semiaxis was about 92 mm in the fingertip case, while it was 24 mm in the stylus case. This means that when writing with the fingertip we get a higher transmission ratio between joint angle variations and end–effector displacement, and indirectly we have a wider workspace. On the other hand, this result shows that when using a stylus to interact with the environment in complex tasks, as writing, it is possible to obtain a higher precision. The

(a) Rotation of the writing plane about the x axis

(b) Rotation of the writing plane about the y axis

Fig. 14. Projections of the kinematic manipulability ellipsoids on the writing plane, when a stylus is used to write and different rotation angles of the writing plane are taken into account.

ratio between the maximum and minimum semiaxis was 9.2 for the fingertip, and about 2.3 for the stylus. Such results reflect the qualitative observation, that appears by comparing Fig. 10 and 13. The kinematic manipulability ellipsoid has a quite spherical shape using a stylus, while it is spindly when the fingertip is adopted to write. In other terms, by writing with a stylus, we obtain a more isotropic kinematic transformation from the joint space to the workspace w.r.t writing with the index fingertip.

This more isotropic behavior obtained using the stylus is also reflected in the projection of the kinematic manipulability ellipsoids on the writing plane. By comparing Fig. 12 and 14, performance, in terms of kinematic manipulability indexes, is clearly less affected by the writing plane orientation when using a stylus.

The difference between the sizes and shapes of the kinematic manipulability ellipsoids between the considered configurations is substantially due to the difference between the kinematic structures. In the first case, when the handwriting task is performed with the fingertip, the equivalent kinematic structure is serial and then the uncertainties, the clearances, and the errors are summed. On the other hand, when the task is performed with a

stylus, the equivalent mechanical scheme is a parallel structure, characterized by higher stiffness and precision [46].

These considerations on manipulability indexes are based only on the kinematic structure of the hand and its posture, so they do not take into account the actual interaction between the stylus/fingertip and the writing plane. In particular such a simplified model did not consider the friction in the writing plane, which may lead to a more complex formulation. This aspect must certainly be integrated into a future work to achieve a more accurate evaluation of the handwriting performance.

In summary, the results obtained with this set of numerical simulations allow us to conclude that writing with the stylus leads to a more isotropic behavior of the kinematic manipulability indexes, and it is possible to control the motion of the stylus tip along all directions with approximately the same effort. The effort required to write with the fingertip, however, sensibly depends on the direction along which we write and on the relative inclination of the writing surface. On the other hand, since the size of the kinematic manipulability ellipsoid is bigger, a larger workspace is reachable by writing with the fingertip.

Referring to the handwriting experiment introduced in Sec. 2, the larger size of the bounding box and the longer path length obtained in the task performed with the fingertip, w.r.t. the ones obtained with the stylus, can be related with the overall dimension of the kinematic manipulability ellipsoids obtained in the numerical simulations. Higher kinematic manipulability constitutes lower precision, so subjects tend to perform the task with a larger size of the bounding box. On the other hand, the numerical results show a more tapered shape of the ellipsoid in the case of writing with the fingertip. In particular, along one of the three directions the kinematic manipulability index is sensibly lower (approximately $1/8$) than in the other two. Along this direction a higher joint displacement is then required to obtain the same movement, which could be, in some cases, difficult to obtain due to joint limits and to the biomechanical structure of the fingertip. It is therefore reasonable to suppose that the subject tends to compensate for this local loss of mobility with a larger motion of the wrist.

However, the role of wrist movement on the overall handwriting performance and its relation with the manipulability analysis are preliminary and need further investigations. A more detailed study, that takes the direction of wrist motion into account, is necessary to verify this hypothesis and it is planned in our next work on this topic. To partially assess this issue, in the following Section another experiment is presented, in which the wrist is kept fixed.
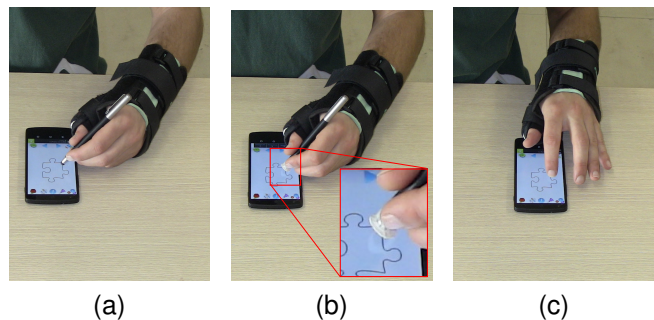

(a) (b) (c)

Fig. 15. Retracing a contour experimental setup. A postoperative brace is used to minimize the participant's wrist movement while she/he is retracing a shape on the screen using (a) the index fingertip, (b) a stylus with a small disk attached to its tip to increase the visual occlusion, and (c) a stylus as it is commercially available. Fourteen volunteers participated in the experiment.

6 EXPERIMENT: RETRACING A COMPLEX CONTOUR

The experiment was devoted to further investigating the consequences of the the numerical results obtained by the numerical simulations. The experimental setup was composed by a smartphone Nexus 5, developed by Google Inc. and LG Electronics, with a screen of 5" diagonal and a resolution of 1080 by 1920 pixels, and a Bamboo Stylus (when required), developed by Wacom Co. and compatible with capacitive touchscreens. The program "123s ABCs Handwriting Fun ZBP" was run on the mobile device and was used to collect data about subjects' handwriting skills.

Fourteen volunteers, ten males and four females, age range 22-41 years, took part in the experiment. Eleven participants were right-handed, three left-handed, and all of them had prior experience using a stylus, and doing finger operations on touchscreen devices. The participants were asked to retrace a shape on the screen using (1) the index fingertip (task F), (2) the provided stylus with a little disk attached to its tip as shown in Fig. 15b (task So), and (3) the stylus as it is commercially available (task S). All the tasks had to be carried out as quickly as possible, but also as accurately as possible. In task So the small disc attached to the stylus tip was used to reproduce the visual occlusion caused by the finger in task F while following the reference shape contour. The disk diameter was 15 mm and remained the same among all the subjects. This size was estimated based on the size of the fingers of five subjects. The considered shape, a puzzle piece (see Fig. 16), was always the same throughout the experiment. Stylus and finger inputs were proposed to subjects in a randomized order until reaching ten trials for each technique. The shape was rotated by 90 degrees clockwise each trial.

Users had to mimic the hand pose analyzed in the previous numerical simulations trying to reproduce, at

the starting configuration, the angle of incidence with the writing plane that achieved best performance in the numerical tests: about 45 degrees for the fingertip and about 60 degrees for the stylus. Such angles are actually rather close to the natural ones when the finger, or a stylus is used to write on a touchscreen.

A postoperative brace was used to minimize the participants' wrist movement and collect data about only the kinematic chains considered in this work (see Fig. 15). The size of the given shape was appropriate to allow users to entirely retrace it although the wrist position was fixed with respect to the table.

Participants could start from the point of the shape they preferred and then proceed to retrace the entire shape either clockwise or counterclockwise.

Participants were informed about the procedure before the beginning of the experiment, and a 5–minute familiarization period was provided to acquaint them with the experimental setup and both the input methods.

Although the numerical simulations have been carried out on a right hand model, because of the symmetry of both the hand and the kinematic manipulability ellipsoids, the use of the left hand in this kind of trial cannot affect the performance. For this reason both right-handed and left-handed subjects could be considered in this experiment.

6.1 Experimental results and discussion

We collected data about (1) the completion time of a task t, and (2) the average error e, in order to evaluate the performance of the tested handwriting methods (task F, task So, and task S) . The task started when the user touched the screen for the very first time and ended when the user lifted the stylus, or the fingertip, from the screen. We computed the error as the sum of the euclidean distances in pixels between each point of the path written by a user and the nearest point belonging to the original black shape. We then averaged the error over the total number of pixels of the black shape, which is constant for all the trials. Different colors were used to identify each writing input mean: green when using the index fingertip, red when using the stylus with the increased visual occlusion and blue, using it without (see Fig. 16).

In order to analyze and compare overall performance of the three input methods considered in this work we computed a performance index as $PI = 100 \left(t \cdot e \right)^{-1}$. It decreases both when the subject is too slow to retrace the given shape and when the user's path differs too much from the original black outline. Data resulting from ten tracing trials, concerning the same writing method and performed by the same subject, were averaged and then compared with the other task's data. Fig. 17a reports the PI values, Fig. 17b shows the time t elapsed between the instant the user touches the screen for the very first time and the instant she/he completes the task, and Fig. 17c reports the error e.
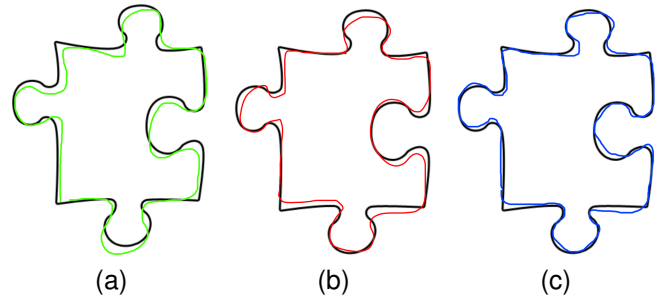

Fig. 16. Smartphone screenshots when the retracing experiment was carried out by a representative subject using (a) the index fingertip (task F), (b) the stylus with an increased visual occlusion (task So), and (c) the stylus as it is commercially available (task S). In this specific example the performance indexes are 0.38, 0.57, and 0.71 when the fingertip, the stylus with increased visual occlusion, and that without were used.

All data are averaged over all the participants and passed the Shapiro-Wilk normality test, then no data transformation was necessary to proceed with a repeated-measures ANOVA. However, since average error data e failed the Mauchlys Test of Sphericity the Greenhouse-Geisser correction was used in this case to correct the degrees of freedom of the F-distribution. Results of Fig. 17a showed a statistically significant difference between the means of the three writing conditions ($F(2, 26) = 73.741$, p< 0.001, a=0.05). Post hoc analysis with Bonferroni adjustments revealed a statistically significant difference among all the conditions (F vs. So, p < 0.001; F vs S, p < 0.001; So vs S, p < 0.001). Similarly completion time data showed a statistically significant difference among the means of the three writing methods ($F(2, 26) = 67.68$, p< 0.001, a=0.05) and a pairwise comparisons with Bonferroni adjustments revealed a statistically significant difference between all the conditions (F vs. So, p < 0.001; F vs S, p < 0.001; So vs S, p = 0.003). Finally the repeated measures ANOVA with a Greenhouse-Geisser correction determined that average error e differed statistically significantly between the proposed writing conditions ($F(1.132, 14.713) = 65.647$, p< 0.001, a=0.05). Post hoc tests using the Bonferroni correction revealed no significant difference between So and S modalities, while it revealed a statistically significant difference in the other cases (F vs. So, p < 0.001; F vs S, p < 0.001).

According to the parameters considered in this work we can conclude that writing on a touchscreen with a stylus leads to better performance than writing with a finger. In task So we tried to compensate the difference in terms of visual occlusion between finger and stylus. PI results show that even though the disc did not allow the participants to clearly see the shape contour to be followed, performance is still better with the stylus than the finger. In Fig. 17c the difference in terms of average
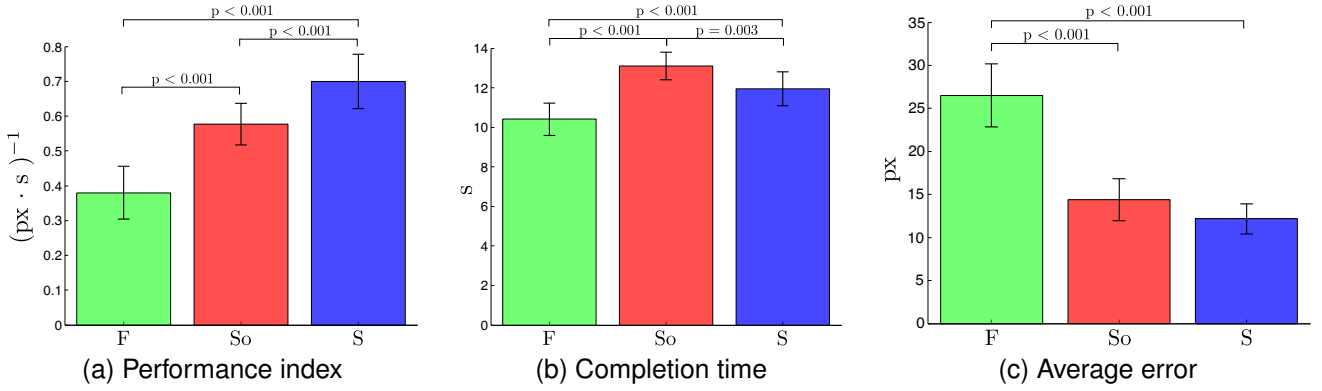
Fig. 17. Retracing a contour experiment. Performance index, completion time, and average error in retracing a given shape for the three writing methods: index fingertip (F), stylus with increased visual occlusion (So), and stylus as it is commercially available (S). The higher the PI index, the better the performance ($PI = 100\,(t \cdot e)^{-1}$). Means and standard deviations are plotted. P-values of Post-Hoc group comparisons are reported when a statistical difference is present (confidence interval of 95%).

error in using the stylus (task S and So) and the finger (task F) is clear. The error is similar performing the task So and S. Fig. 17b shows that the larger visual occlusion in task So, compared to the one in task S, leads users to be slower in tracing the entire shape outline. Perhaps participants tried to make up for the lack of visual information by slowing down their movements. This behavior did not occur when the finger was used.

In the preceding Section we observed that task F is characterized by a kinematic manipulability ellipsoid with a larger volume and a more tapered shape w.r.t. task S. Introducing manipulability analysis, we furthermore observed that the kinematic manipulability index can be interpreted as a measure of both the velocity and the error amplification from the joint space to the end-effector space. Qualitatively comparing the numerical results discussed in Sec. 5 with those obtained in this experiment, we observe that they are in agreement: both the reduced completion time and the increased average error obtained in the task F w.r.t. S can be explained with the large overall dimension of the kinematic manipulability ellipsoid. However, these results are still preliminary, and the research of a quantitative correlation between the results of numerical simulations and experimental measures is in progress.

7 CONCLUSION AND FUTURE WORK

In this paper we investigated and compared the digital handwriting task with the index fingertip and with a stylus, explicitly taking into account the biomechanics and the kinematic of the human hand. The study has been performed by both developing an analytic/numerical model and carrying out some experiments.

The kinematic structure of the hand was the starting point of our analysis. In this study a 20 DoF model has been chosen to model the human hand, since it was a good trade–off between simplicity and accuracy

in the representation of hand posture and movements. We chose the manipulability analysis, widespread in robotics to evaluate performance in terms of velocity transformations, as a methodological tool that takes into account the hand kinematics.

By applying manipulability analysis to the human hand performing handwriting tasks, we observed that when writing with the fingertip we obtain a kinematic manipulability ellipsoid about 4 times larger in terms of maximum semiaxis w.r.t. that achieved with the stylus. Furthermore, if we consider the task carried out with the stylus, the resulting kinematic manipulability ellipsoid has semiaxes of more similar length, so the kinematic transformation from the hand joints to the end–effector is more isotropic than the one obtained considering the fingertip handwriting. These results confirm the intuitive consideration that using a stylus allows one to reach a more accurate and precise control of writing.

Even though this may seem an intuitive result, our analysis provides quantitative data concerning specific parameters, e.g. motion isotropy, and principal directions of motion, which are hard to compute and evaluate without a thorough examination. In this work we also developed mathematical tools that allow the analysis of other aspects of digital handwriting, such as the dependency of writing performance on hand biomechanical properties, or on hand postures.

Moreover we presented two experiments conducted in a real digital handwriting scenario, devoted to further analyzing the task and to verify the potential and thoroughness of the numerical model and simulations. In the first one subjects were asked to write two words on a tablet, while in the second one they had to retrace a given shape on a touchscreen. In both the experiments they had to use either the index fingertip or a stylus to accomplish the proposed tasks. In a task of the second experiment we reproduced with the stylus the visual occlusion generated by the size of the fingertip adding

a small disc on the stylus tip.

With the handwriting experiment we aimed at collecting information on characteristics of the written words in a free digital handwriting task. In this experiment we measured the words bounding box, the participants' wrist motion, and the path length. In the second experiment we quantified handwriting performance by using some different metrics, such as average error and completion time. In the experiments in which the subjects were asked to retrace a given shape on a touchscreen, we evaluated a mean Performance Index PI, proportional to the execution velocity and accuracy. We observed that when using the finger its value is approximately one–half (50%) than when using a stylus. In free handwriting tasks we observed a reduction of the wrist displacement ($\simeq 25\%$), a reduction of the bounding box size ($\simeq 30\%$), and a reduction of the path length ($\simeq 30\%$) by using a stylus rather than using the fingertip.

The main trend of the experimental results showed that when using a stylus to write on a tablet leads to a more precise and efficient control: the written text bounding box, the written path, and the wrist overall displacement are significantly smaller when writing with a stylus than when writing with the fingertip. The experimental results, in terms of precision, do not significantly depend on the size of the contact patch: the occlusion between the writing tool (the finger or the stylus) and the writing surface affects only the task completion time. The accuracy observed in the experiment mainly depends on the input type: the average error obtained in a retracing task carried out with a stylus is approximately one–half of that obtained with the finger, even considering the occlusion effect.

Globally the experimental results present the same trends as the numerical simulation ones, and therefore justify and support the proposed approach, even though some aspects, e.g. wrist motion, have to be further investigated. Using a stylus is in general more convenient for performing precision tasks, such as drawing, painting, writing, signing a document, etc., while a fingertip interaction is more suitable in tasks with a wide workspace and where a lower precision is required, for example selecting icons, navigating in a map, answering a call, etc..

The theoretical and numerical evaluation tools could be improved by adopting more complete hand models, with a higher number of DoF, and including the mechanical model of the tendinous-muscular apparatus of the hand. In the numerical simulations, it would be furthermore interesting to consider different hand dimensions and postures.

Concerning the experimental results analysis, in this work we did not consider people's habits. From a very young age, people begin to write with a pen, or a pencil, while only recently the act of writing with the fingertip has spread. We suppose that this could be a reason why people feel more comfortable using a tool rather than a finger to write and this can obviously affect writing performance.

Further investigation will involve the distribution of contact forces during writing operations, the pressure applied to the stylus through the hand, and the relationship between hand and arm motion. Moreover the use of a finger as a stylus, i.e., supported by another finger, will be investigated. A study on how different sizes of the contact patches and different occlusion effects might affect handwriting performance will be certainly carried out. A handwriting recognition technique can also be adopted to examine the influence of the use of the stylus and the fingertip on word legibility.

This study provides tools that can be useful to complete and integrate the existing handwriting studies with quantitative performance evaluations. Such tools could also be useful to design new input devices to interact with active surfaces. In our opinion this aspect is crucial, due to the great diffusion of devices, such as tablets, smartphones, etc., in which the interaction in question is required.

REFERENCES

[1] L. A. Jones and S. J. Lederman, *Human hand function*. Oxford University Press, USA, 2006.

[2] F. N. Freeman, *The Handwriting Movement: A Study of the Motor Factors of Excellence in Penmanship*. The University Press, 1918.

[3] L. R. B. Schomaker and R. Plamondon, "The relation between pen force and pen-point kinematics in handwriting," *Biological Cybernetics*, vol. 63, no. 4, pp. 277–289, 1990.

[4] S. Edelman and T. Flash, "A model of handwriting," *Biological Cybernetics*, vol. 57, no. 1-2, pp. 25–36, 1987.

[5] J. Hermsdörfer, C. Marquardt, A. S. Schneider, W. Fürholzer, and B. Baur, "Significance of finger forces and kinematics during handwriting in writer's cramp," *Human movement science*, vol. 30, no. 4, pp. 807–817, 2011.

[6] A. W. Hooke, J. Park, and J. K. Shim, "The forces behind the words: Development of the kinetic pen," *Journal of biomechanics*, vol. 41, no. 9, pp. 2060–2064, 2008.

[7] J. K. Shim, A. W. Hooke, Y. S. Kim, J. Park, S. Karol, and Y. H. Kim, "Handwriting: Hand–pen contact force synergies in circle drawing tasks," *Journal of biomechanics*, vol. 43, no. 12, pp. 2249–2253, 2010.

[8] A. Kushki, H. Schwellnus, F. Ilyas, and T. Chau, "Changes in kinetics and kinematics of handwriting during a prolonged writing task in children with and without dysgraphia," *Research in Developmental Disabilities*, vol. 32, no. 3, pp. 1058–1064, 2011.

[9] T. Falk, C. Tam, H. Schwellnus, and T. Chau, "Grip force variability and its effects on children's handwriting legibility, form, and strokes.," *Journal of Biomechanical Engineering*, vol. 132, no. 11, pp. 1–17, 2010.

[10] A. Holzinger, G. Searle, B. Peischl, and M. Debevc, "An answer to "who needs a stylus?" on handwriting recognition on mobile devices," in *E-Business and Telecommunications*, pp. 156–167, 2012.

[11] H. Tu, X. Ren, and S. Zhai, "A comparative evaluation of finger and pen stroke gestures," in *Proc. ACM Int. Conf. on Human Factors in Computing Systems*, pp. 1287–1296, ACM, 2012.

[12] D. Vogel and P. Baudisch, "Shift: a technique for operating pen-based interfaces using touch," in *Proc. ACM Int. Conf. on Human Factors in Computing Systems*, pp. 657–666, 2007.

[13] P. Brandl, C. Forlines, D. Wigdor, M. Haller, and C. Shen, "Combining and measuring the benefits of bimanual pen and direct-touch interaction on horizontal interfaces," in *Proc. ACM Int. Working Conf. on Advanced Visual Interfaces*, pp. 154–161, 2008.

[14] K. Hinckley, K. Yatani, M. Pahud, N. Coddington, J. Rodenhouse, A. Wilson, H. Benko, and B. Buxton, "Pen+ touch= new tools," in *Proc. 23rd ACM Symp. on User Interface Software and Technology*, pp. 27–36, 2010.

[15] J. Alston, "A legibility index: can handwriting be measured?," *Educational Review*, vol. 35, no. 3, pp. 237–242, 1983.

[16] S. Zabramski, "Careless touch: a comparative evaluation of mouse, pen, and touch input in shape tracing task," in *Proc. ACM 23rd Australian Computer-Human Interaction Conference*, pp. 329–332, 2011.

[17] V. Potkonjak, M. Popovic, M. Lazarevic, and J. Sinanovic, "Redundancy problem in writing: from human to anthropomorphic robot arm," *IEEE Trans. on Systems, Man, and Cybernetics, Part B: Cybernetics*, vol. 28, no. 6, pp. 790–805, 1998.

[18] V. Potkonjak, "Robotic handwriting," *International Journal of Humanoid Robotics*, vol. 2, no. 01, pp. 105–124, 2005.

[19] V. Potkonjak, V. M. Petrovic, K. Jovanovic, and D. Kostic, "Human-robot analogy-how physiology shapes human and robot motion," in *Advances in Artificial Life, ECAL*, vol. 12, pp. 136–143, 2013.

[20] J. K. Salisbury, *Kinematic and Force Analysis of Articulated Hand*. PhD thesis, Stanford University, Department of Mechanical Engineering, May 1982.

[21] T. Yoshikawa, "Manipulability of robotic mechanisms," *International Journal of Robotics Research*, vol. 4, pp. 3–9, June 1985.

[22] J. K. Salisbury and J. J. Craig, "Articulated hands, force control and kinematic issues," *International Journal of Robotics Research*, vol. 1, no. 1, pp. 4–17, 1982.

[23] A. Bicchi and D. Prattichizzo, "Manipulability of cooperating robots with unactuated joints and closed-chain mechanisms," *IEEE Trans. Robotics and Automation*, vol. 16, no. 4, pp. 336–345, 2000.

[24] H. Kato and M. Billinghurst, "Marker tracking and hmd calibration for a video-based augmented reality conferencing system," in *Proc. IEEE and ACM 2nd Int. Workshop on Augmented Reality*, pp. 85–94, 1999.

[25] A. M. Swartz, S. J. Strath, D. R. Bassett, W. L. O'Brien, G. A. King, and B. E. Ainsworth, "Estimation of energy expenditure using csa accelerometers at hip and wrist sites," *Medicine and Science in Sports and Exercise*, vol. 32, no. 9; SUPP/1, pp. S450–S456, 2000.

[26] S. Mulatto, A. Formaglio, M. Malvezzi, and D. Prattichizzo, "Using postural synergies to animate a low-dimensional hand avatar in haptic simulation," *IEEE Trans. on Haptics*, vol. 6, no. 1, pp. 106–116, 2013.

[27] G. Gioioso, G. Salvietti, M. Malvezzi, and D. Prattichizzo, "Mapping synergies from human to robotic hands with dissimilar kinematics: an approach in the object domain," *IEEE Trans. on Robotics*, vol. 29, no. 4, pp. 825–837, 2013.

[28] D. Prattichizzo, M. Malvezzi, M. Gabiccini, and A. Bicchi, "On motion and force controllability of precision grasps with hands actuated by soft synergies," *IEEE Transactions on Robotics*, vol. 29, no. 6, pp. 1440–1456, 2013.

[29] K. Kim, Y. Youm, and W. K. Chung, "Human kinematic factor for haptic manipulation: The wrist to thumb," in *Proc. IEEE 10th Symp. on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp. 319–326, 2002.

[30] Y. Youm, M. Holden, and K. Dohrmann, "Finger ray ratio study," in *Technical report on Wrist project No. 10*, 1977.

[31] G. Stillfried and P. van der Smagt, "Movement model of a human hand based on magnetic resonance imaging (mri)," in *Proc. IEEE Int. Conf. on Applied Bionics and Biomechanics*, pp. 14–16, 2010.

[32] S. Cobos, M. Ferre, S. Uran, J. Ortego, and C. Pena, "Efficient human hand kinematics for manipulation tasks," in *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 2246–2251, 2008.

[33] S. Cobos, M. Ferre, and R. Aracil, "Simplified human hand models based on grasping analysis," in *Proc. Intelligent Robots and Systems (IROS)*, pp. 610–615, 2010.

[34] G. Wu, F. C. Van der Helm, H. Veeger, M. Makhsous, P. Van Roy, C. Anglin, J. Nagels, A. R. Karduna, K. McQuade, and X. Wang, "Isb recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion–part ii: shoulder, elbow, wrist and hand," *Journal of biomechanics*, vol. 38, no. 5, pp. 981–992, 2005.

[35] D. Prattichizzo and J. Trinkle, "Grasping," in *Handbook on Robotics* (B. Siciliano and O. Kathib, eds.), pp. 671–700, 2008.

[36] F. J. Valero-Cuevas, "An integrative approach to the biomechanical function and neuromuscular control of the fingers," *Journal of biomechanics*, vol. 38, no. 4, pp. 673–684, 2005.

[37] D. G. Kamper, H. C. Fischer, and E. G. Cruz, "Impact of finger posture on mapping from muscle activation to joint torque," *Clinical Biomechanics*, vol. 21, no. 4, pp. 361–369, 2006.

[38] G. Baud-Bovy, D. Prattichizzo, and N. Brogi, "Does torque minimization yield a stable human grasp?," *Workshop on Multi-point interaction in Robotics and Virtual Reality, ICRA*, 2004.

[39] J. Levy, "A review, analysis, and some new data on hand-posture distributions in left-handers," *Brain and cognition*, vol. 3, no. 2, pp. 105–127, 1984.

[40] R. D. Howe and A. Z. Hajian, "Identification of the mechanical impedance at the human finger tip," *Journal of biomechanical engineering*, vol. 119, pp. 109–114, 1997.

[41] L. Sciavicco and B. Siciliano, *Modelling and control of robot manipulators*. 2001.

[42] R. Murray, Z. Li, and S. Sastry, *A mathematical introduction to Robotic Manipulation*. 1994.

[43] D. Prattichizzo, M. Malvezzi, M. Gabiccini, and A. Bicchi, "On the manipulability ellipsoids of underactuated robotic hands with compliance," *Robotics and Autonomous Systems*, vol. 60, no. 3, pp. 337–346, 2012.

[44] A. Bicchi and D. Prattichizzo, "Manipulability of cooperating robots with passive joints," in *Proc. IEEE Int. Conf. on Robotics and Automation*, (Leuven, Belgium), pp. 1038–1044, May 1998.

[45] M. Malvezzi, G. Gioioso, G. Salvietti, and D. Prattichizzo, "Syngrasp: A matlab toolbox for underactuated and compliant hands," *IEEE Robotics and Automation Magazine*, 2015. In press.

[46] L. W. Tsai, *Robot analysis: the mechanics of serial and parallel manipulators*. John Wiley & Sons, 1999.

Domenico Prattichizzo (S'93 - M'95) received the M.S. degree in Electronics Engineering and the Ph.D. degree in Robotics and Automation from the University of Pisa in 1991 and 1995, respectively. Since 2002 Associate Professor of Robotics at the University of Siena. Since 2009 Scientific Consultant at Istituto Italiano di Tecnologia, Genova, Italy. In 1994 Visiting Scientist at the MIT AI Lab. Coauthor of the Grasping chapter of Handbook of Robotics, 2008, awarded with two PROSE Awards presented by the American Association of Publishers. Since 2007 Associate Editor and Chief of the IEEE Trans. on Haptics. From 2003 to 2007 Associate Editor of the IEEE Trans. on Robotics and IEEE Trans. on Control Systems Technologies. Vice-chair for Special Issues of the IEEE Technical Committee on Haptics (2006-2010). Chair of the Italian Chapter of the IEEE RAS (2006-2010), awarded with the IEEE 2009 Chapter of the Year Award. Co-editor of two books by STAR, Springer Tracks in Advanced Robotics, (2003, 2005). Coordinator of the European project "WEARHAP-WEARable HAPtics for humans and robots." Research interests are in haptics, grasping, visual servoing, mobile robotics, and geometric control. Author of more than 200 papers in these fields.

Leonardo Meli (S'13) received the M.S. degree cum laude in computer engineering in 2012 from the University of Siena, Italy. He was an exchange student at the Karlstad University, Sweden in 2010. He is currently a Ph.D. student at the Dept. of Information Engineering and Mathematics of the University of Siena and at the Dept. of Advanced Robotics of the Italian Institute of Technology. His research interests include robotics and haptics focusing on cutaneous force feedback techniques, teleoperation systems for medical applications and grasping.

Monica Malvezzi (M'12) is Assistant Professor of Mechanics and Mechanism Theory at the Dipartimento di Ingegneria dell'Informazione e Scienze Matematiche of the University of Siena. She got the Laurea degree in Mechanical Engineering from the University of Florence in 1999 and and the Ph.D. degree in Applied Mechanics from the University of Bologna in 2003. From 2003 to 2008 she was researcher at the University of Florence, where she collaborated with the MDM lab (Laboratorio di Modellazione Dinamica e Meccatronica). Her main research interests are in mechanism theory, control of mechanical systems, robotics, vehicle localization, multibody dynamics, haptics, grasping and dexterous manipulation. She is author of more than 80 papers in these fields.