ThimbleSense: an individual-digit wearable tactile sensor for experimental grasp studies

Edoardo Battaglia, Giorgio Grioli, Manuel G. Catalano, Marco Santello and Antonio Bicchi

***Abstract*— Measuring contact forces applied by a hand to a grasped object is a necessary step to understand the mysteries that still hide in the unparalleled human grasping ability. Nevertheless, simultaneous collection of information about the position of contacts and about the magnitude and direction of forces is still an elusive task. In this paper we introduce a wearable device that addresses this problem, and can be used to measure generalized forces during grasping. By assembling two supports around a commercial 6-axis force/torque sensor we obtain a thimble that can be easily positioned on a fingertip. The device is used in conjunction with an active marker-based motion capture system to simultaneously obtain absolute position and orientation of the thimbles, without requiring any assumptions on the kinematics of the hand. Finally, using the contact centroid algorithm, introduced in [1], position of contact points during grasping are determined. This paper shows the design and implementation of the device, as well as some preliminary experimental validation.**

I. Introduction

The human hand has a complicated structure and a high number of degrees of freedom. Despite this underlying complexity, experimental evidence suggested through the years that, within the space of all the possible configurations, only a few basic movements, normally referred to as synergies, explain the postures assumed while grasping typical objects [2]. This concept does not apply only to postures, but also to finger contact forces [3]: the phenomenon appears to extend through the whole neuromuscular system [4]. Synergies have an immediate and practical application in the construction of robotic hands, since they can be used to simplify design and control of what would otherwise be a very complex system [5]. Measurements related to the human hand kinematics and dynamics are a fundamental prerequisite for the study of synergies. However, while several works address measurement and estimation of posture (see for example [6]-[7]), force related measurements provide a greater challenge, especially when the goal is to obtain complete information regarding both force and torque. This is often achieved by using sensorized objects [8], that can either compel grasping from predetermined locations, as in [3], or leave the possibility of a more generic grasping configuration, as in [9], even if this sometimes comes at the cost of sacrificing the number of possible contacts between the hand and the object.

An alternative approach consists in applying sensors directly on the hand, to favor versatility: this can be accomplished by using gloves (see [10] for some examples)

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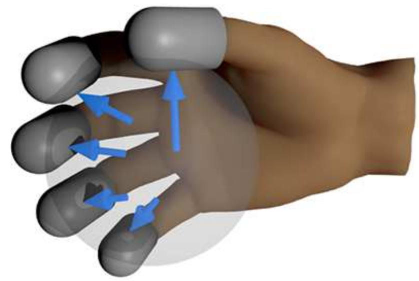
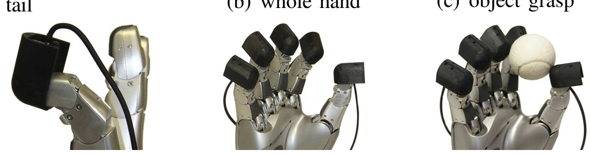


Fig. 1. Concept of the *ThimbleSense* digit-wearable tactile sensor.

which, however, usually use pressure sensors, and thus do not provide any information regarding shear forces. More advanced approaches exist that measure forces while leaving the fingerpad free from occlusion: in [11] the relationship between nail strain and compression forces on the fingerpad was studied, while in [12] the horizontal deformation of fingerpads was used to estimate normal forces. In [13] fingernail sensors were introduced that correlate blood distribution under the finger nail with forces, which later publications further developed and refined (see for example [14]). This last solution is particularly interesting since it also provides measurements for shear forces, however, it requires fine calibration and, to the best of our knowledge, currently provides no information regarding the position of contact points.

This work presents the *ThimbleSense*, a design for a sensor system which can be worn on fingertips and gives complete measurement of all components of generalized forces applied upon grasped objects. This is achieved by combining a commercial six axis force/torque sensor with a pair of support shells, blending the two conventional approaches by building a wearable sensorized object. To obtain position and orientation of the system we integrate the sensors with a high-speed camera-based active motion capture system, which provides a convenient and precise



(a) fingertip detail (b) whole hand (c) object grasp

Fig. 2. Example of application on a robotic hand: the *ThimbleSense* wearable force/torque measuring device is placed on the distal phalanges of the DLR Hand II.

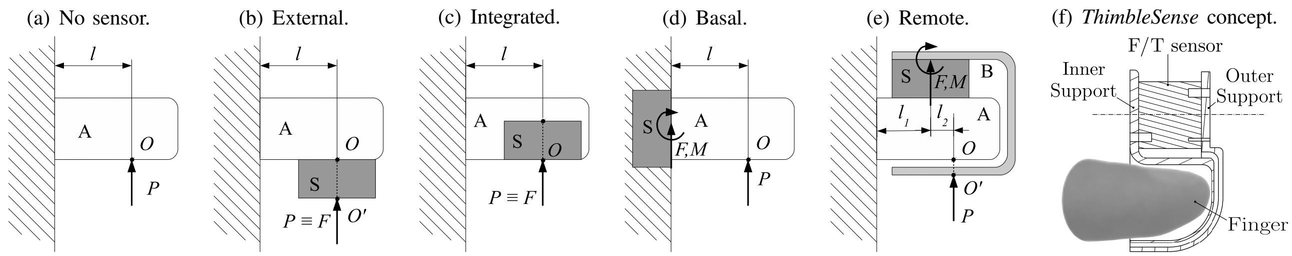


Fig. 3. A basic loaded structure (a), possible ways to sense the load (b-e), and the concept behind our shell-based wearable design (f).

way to measure position. By using the algorithm proposed in [1], it is possible to determine the position on the thimble of the centroid of contact with the object being touched: it is worth pointing out that torque measurements, as those provided by the *ThimbleSense*, are necessary to apply this algorithm. Combination of all this information provides full reconstruction of grasp forces vectors, in terms of magnitude, direction and application point.

The proposed design can also be easily applied to existing robotic hands (as shown e.g. in fig. 2), enabling precise online measurement of contact forces and contact position, without re-designing and replacing the usually costly hardware components of the robot.

II. Problem Definition

The measurement of forces and torques on a fingertip can be cast as a generic structural mechanics problem. To try and analyze the possible solutions let us abstract from the physical problem at state, and consider the simple 2D example shown in Fig. 3(a). A rigid body $\mathbf{A}$, attached to a frame, withstands a force P applied on a point O at position l, perpendicularly with respect to its main axis. Let us suppose that a sensor $\mathbf{S}$, able to measure force F and torque M applied on its surface, is available. The simplest course of action to measure the applied force is interjecting the sensor between the applied force and the object $\mathbf{A}$, as in fig. 3(b). This solution, which is in general possible only when the position l is known *a-priori*, has the disadvantage of dislocating the point in which the force P is applied from the original O to the remote O'. This displacement could be recovered by excavating a hole inside the object $\mathbf{A}$ and using it to integrate the sensor (fig. 3(c)); or it could be removed altogether by splitting the structure in two parts, separating body $\mathbf{A}$ from the frame and interposing the sensor between them, as in fig. 3(d). This would allow, from the measurements of force F and torque M, the straightforward reconstruction of $P = F$ and $l = \frac{M}{P}$, and thus of both the *magnitude* and *position* of the contact force. It is worth pointing out that without torque measurement it would not be possible to estimate the position of the contact.

The three approaches exposed so far lead the design of common sensorized objects, but they can not be applied to a human finger: approaches 3(c) and 3(d) are invasive with respect to the finger, while approach 3(b) is invasive with respect to the grasp itself, owing to the typical dimensions of force/torque sensors. The problem can then be defined as designing a sensor capable of results similar to those obtainable with approach 3(d) (simultaneous reconstruction of force and contact position), which can be placed on the finger without completely altering the grasp with interposition of a cumbersome object between the finger and the contact. Fig. 3(e) shows a possible solution : by assembling the sensor $\mathbf{S}$ between the object $\mathbf{A}$ and a properly designed shell $\mathbf{B}$ we obtain a system which is completely non-invasive to the finger, while also minimizing alteration to the way the load is applied. In this regard it can be noticed that, as in solution 3(b), the load is not directly applied on point O but on a different point O'; however, contrarily to solution 3(b), a proper design of the shell $\mathbf{B}$ can substantially contain the distance $\overline{OO'}$. This last solution was selected for our device and led to the concept of fig. 3(f). The next section shows how this concept is transformed into a design and physically built.

III. Our Approach

The concept behind the design of the *ThimbleSense* is as follows: a F/T sensor is assembled between an inner and an outer shell separated by a gap. The finger finds its accomodation inside the inner shell, and once the outer shell gets in contact with an object the action applied is routed though the sensor, which constitutes the only mechanical coupling element between the two shells. Owing to this a complete measurement of forces and torques can be obtained: thus, since geometry of the external support is known, it is possible to obtain the position of the contact centroid of the loading force P, through the algorithm defined in [1].

A number of factors must be taken into account to obtain a functional design, namely:

- *Size*: the device must be as small as possible, to minimize encumbrance. Consequently, all layers between the finger and the external surface of the outer shell must be as thin as possible; at the same time they need to be thick enough to keep the outer shell separated from the inner shell when a load is applied (for a contact between the two would invalidate the measurement).
- *Weight*: the device needs to be light, to minimize the effort necessary to move it. For this reason a material with a high stiffness/weight ratio should be chosen.
- *Ergonomics*: the device must be shaped in such a way as to leave finger movements unhindered, as much as it is possible.

Overall, the grasping process should ideally be unaffected, and it should be possible to seamlessly place five devices, one on each finger, without them excessively interfering with hand movements and grasping capabilities. However, it is

(a) Model of load. (b) Results.

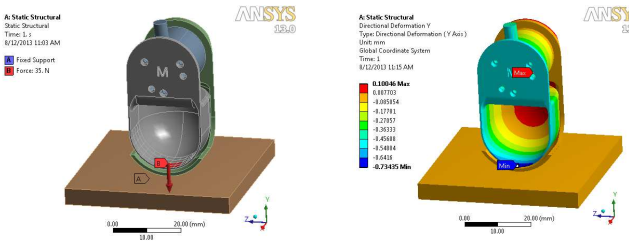


Fig. 4. FEM analysis: load on the inner shell.

(a) Model of load. (b) Results.

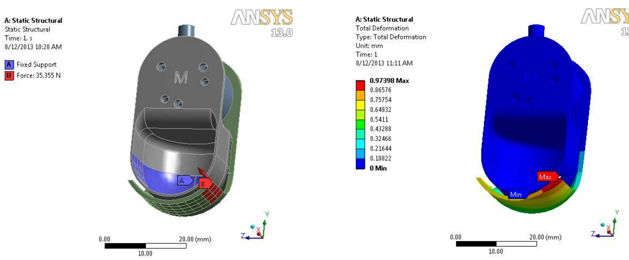
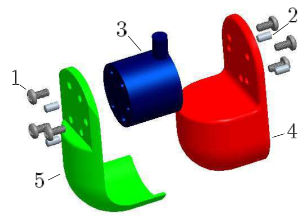


Fig. 5. FEM analysis: load with lateral component on the outer shell.

(a) CAD model (exploded view).



(b) Components.

Number	Name
1	6 Screws m2x4
2	6 Dowel pins 2x4
3	ATI Nano 17
4	Inner shell
5	Outer shell

Fig. 6. Shell based wearable device: final design.

natural to expect that wearing a rigid shell over the finger will somehow alter the grasping process: this problem has been subject of study in [15], where it was shown that wearing a rigid shell on fingers significantly alters haptic recognition of common objects. We acknowledge that this is going to be an intrinsic limitations of our design: however, in this paper we hope to show how it is still possible to perform everyday tasks while wearing the device. We reserve a more thorough verification of this particular aspect for later work.

IV. Mechanical Design

To finalize the mechanical design of the *ThimbleSense* shells, the ATI nano 17 six axis F/T sensor was selected.

Because of its high stiffness/weight ratio, the material chosen to build the thimbles is aluminium. In an attempt to minimize weight and encumbrance of the device, a Finite Element Analysis (FEA) is performed on the CAD model of the device, with the aim of finding the minimum thickness for the shells and the gap, still guaranteeing the shells separation when they elastically deform under load application.

To perform FEA, a load model is introduced. From some basic tests performed by pressing a finger on a high precision scale, reasonable bounds of the forces applied were estimated. An average value for the force was found to be 10 N, while 35 N appeared as a superior limit, achieved only through an extreme effort. In an attempt to be conservative, loads on the structure were modeled as localized forces applied on the bottom surface of the open ends of either the inner and the outer shell.

A custom model has been defined to describe the sensor mechanical properties, with elastic modulus coherent to the elastic constants obtained from the data sheet of the sensor. Trials were performed for various thicknesses: we show here results for a design where thickness is 1 mm for both shells and the gap. Fig. 4 shows a static structural model with a localized force applied on the inner shell. It can be seen that the simulation result shows deformations smaller than 1 mm: since the load model chosen is by far an overestimation of the actual load, this seems to be adequate from a mechanical point of view. In Fig. 5 a load model where a force is applied on the outer shell is shown. In this case the force also presents a significant lateral component. The deformation is close to 1 mm, which is considered to be acceptable owing to the high load, and the fact that this sensor is designed to work with forces having a low lateral component.

It is worth noting that it would not be desirable to have a thicker shell, since that would cause greater weight and encumbrance. On the other hand, reducing the thickness could cause the shells to come in contact when a load is applied. The result of our design procedure can be seen in Fig. 6, which shows an exploded view of the final CAD model, together with the list of components of one *ThimbleSense*.

Different people have different sizes for their fingers, moreover, a significant difference in size is present also between different fingers of the same hand. The experiments in this paper are preliminary in their nature, and use a single

Fig. 7. Glove used to keep thimbles on fingertips.

(a) CAD model. (b) Physical realization.

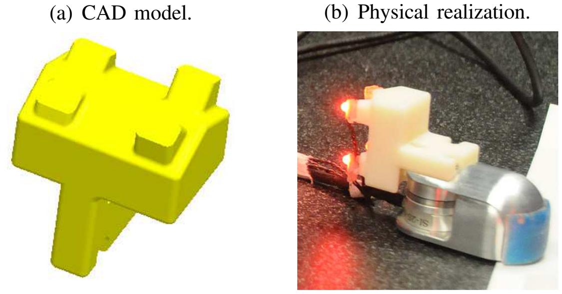


Fig. 8. ABS support for Phase Space markers.

test subject. For this reason only two thimble sizes were necessary: a larger one (25 mm diameter for the interior of the inner thimble) for the thumb, and a smaller one (21 mm diameter) for the other fingers. Designing and building additional sizes is planned as future work.

Grasping objects with a smooth, metal thimble is not an easy task due to the low friction. To restore friction to levels comparable with those of human skin, a friction surface was applied to the outer shell in order to mimic the natural friction behavior of human skin. The friction surface is made of double sided sticky tape covered with a masking paint mixed with fine grain sand: it can be seen in Fig. 8(b).

The *ThimbleSense* is now designed: however, we still need a reliable way to place it on fingertips. Ideally, we would like the inner surface of the thimble to be perfectly attached to the skin. To try and minimize the relative movement between the device and the hand, a fabric glove is designed with female velcro over fingertips, while male velcro is applied to the inside of the *ThimbleSense* (Fig. 7). Moreover, elastic bands are tied around fingers to prevent movement of the fabric and increase stability. This component is what makes the device wearable, and it is used to interface hand and thimbles in the experiments shown in section VI.

V. Position and Orientation Estimation

The developed design allows to measure generalized forces applied to a thimble, which is worn on fingertips while grasping objects. However, the measurements from the F/T sensor are expressed in a frame that is attached to the thimble itself. To locate the contact data in a global reference frame a way to obtain position and orientation of the thimbles is needed.

Position and orientation of a rigid body can be estimated from the position of a number of points attached to it [16]. A possible way to obtain coordinates of points attached to the thimble is by using a motion capture system and placing LED markers on a support attached to the thimble. In our setup, we chose the Phase Space motion capture system [17], and designed and realized suitable ABS plastic supports to attach to the thimbles the LED beacons, which are all uniquely identified by the system through an ID.

To make sure that the minimum number of three markers needed to estimate rigid body motion is always available, four marker slots are designed on the support, so that it is acceptable for the motion capture system to occasionally drop tracking of one marker during acquisition. Such slots are all placed at different heights over the surface of the support, to maximize visibility. The CAD model and physical realization are shown in Fig. 8.

VI. Experimental Validation

In this section we proceed to show some preliminary experiments that make use of the full capabilities of our device. All the sensors used in all experiments have SI-50-0.5 calibration (see [18] for more details).

A. Reconstruction of contact forces and positions on the thimble

In this experiment, a first validation of the device is performed to have a qualitative estimation of the accuracy of force/torque measurements and of the contact point estimation algorithm. To do that, we apply some medical tape on the external surface of the fingertip device, with six points marked, as shown in Fig. 9(a). The thimble is then placed on a finger, which lays on a fixed support (Fig. 9(b)): the points are pressed with a sharp tool (a pen), in the order shown in Fig. 9(a). The measurements are read during the task through a LabVIEW VI, which allows to obtain a sampling rate of 1 kHz.

Fig. 9 shows the results of this experiment. Fig. 9(c) shows contact points with forces applied for six samples of time, one for each target. Fig. 9(e) , 8(f) and 9(g) show components for forces and torques applied in the contact point, and contact point coordinates (for the samples where they are available), as expressed in the reference frame $\{\mathsf{F}\}$.

Intervals of time when there is a contact on the sensor surface can be clearly identified in Fig. 9(e) and 9(g): after a short transient, contact point coordinates stabilize to a steady value. The visual feedback from reconstruction in Fig. 9(c) is realistic: to validate this numerically in Fig. 9(h) we show mean values of all the components, together with variance reconstruction of initiation and termination times of the contact. It can be seen how the contact point estimate is fairly stable once the contact itself is in its steady state.

B. Complete contact forces and positions reconstruction during grasp

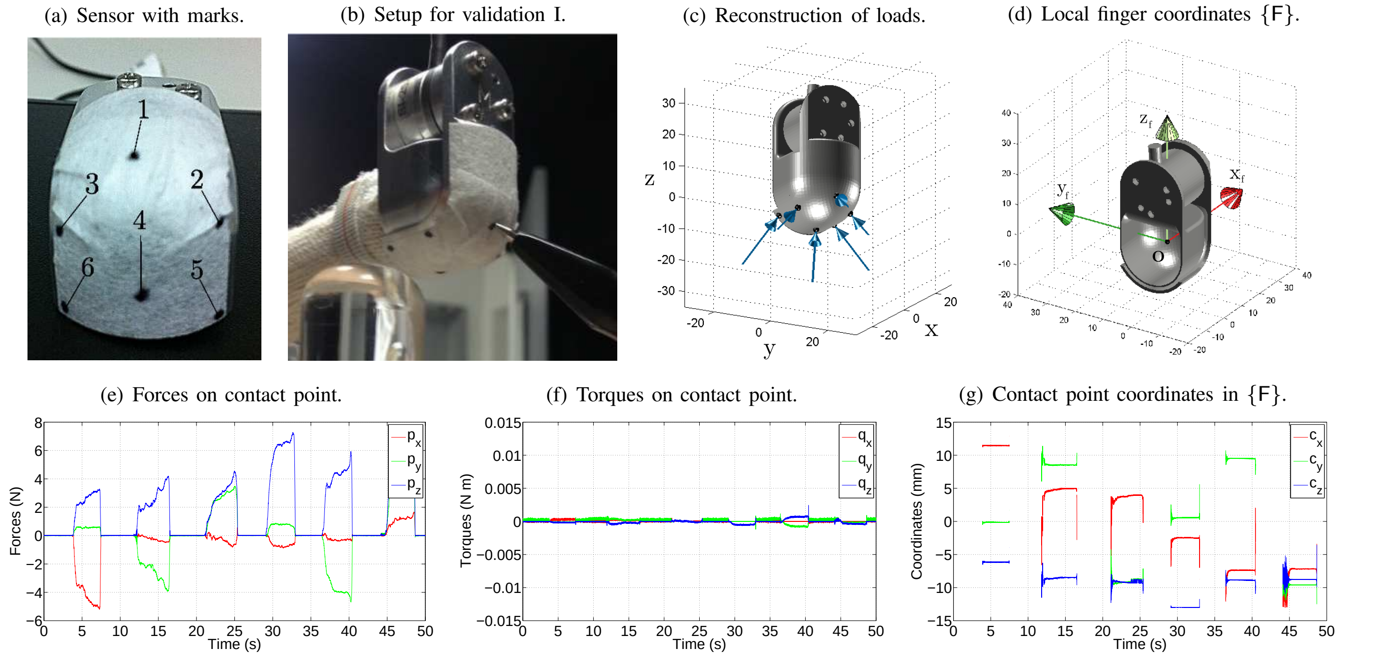
This second experiment shows a qualitative reconstruction of postures of the thimbles and of applied forces. For this purpose, a subject wears the *ThimbleSense* while executing five tasks that involve objects of different shapes. The five tasks are designed to carry different degrees of challenge for the device. Fig. 10 shows the objects used for the five tasks with main dimensions (in mm), as well as the task execution and the reconstruction of the contact forces and positions. Please refer to that figure for the following discussion.

The first task is a basic one: the subject is simply required to lift a light (46.7 grams) ball. While this task does not present a particular degree of challenge for the device, it can be interesting to see in Fig. 10(k) the opposition between the force applied by the thumb and forces applied by other fingers.

The second task has the subject lift a soft paper cup partially filled with water (mass 168.8 grams). The challenge is slightly higher for this task, since more careful control of forces is required to avoid excessive deformation. As in the previous task, the reconstruction seems plausible and opposition can again be noticed between the force exerted by the thumb and those by the other fingers.

In the third task a partially filled bottle with a screw cap needs to be opened (mass 251.3 grams). The degree of challenge here is substantially higher compared to the first two tasks, since a nimbler movement needs to be performed to open the bottle. Fig. 10(m) shows reconstruction of postures and forces: view from the bottom allow to notice how the three forces act in order to exert a net torque on the bottle cap.

The fourth task consists in lifting a one dollar coin (mass 8 grams) placed on a small support. This task is challenging



(a) Sensor with marks. (b) Setup for validation I. (c) Reconstruction of loads. (d) Local finger coordinates {F}.

(e) Forces on contact point. (f) Torques on contact point. (g) Contact point coordinates in {F}.

(h) Contact point statistics.

Point	Start	End	X component		Y component		Z component	
			Mean	Variance	Mean	Variance	Mean	Variance
1	4.0 s	7.4 s	11.5 mm	$1.93\ 10^{-4}$ mm^2	-0.13 mm	$5.97\ 10^{-4}$ mm^2	-6.14 mm	$6.77\ 10^{-4}$ mm^2
2	12.3 s	16.4 s	4.83 mm	$2.51\ 10^{-2}$ mm^2	8.52 mm	$1.43\ 10^{-3}$ mm^2	-8.54 mm	$7.27\ 10^{-3}$ mm^2
3	21.4 s	25.4 s	3.75 mm	$7.66\ 10^{-2}$ mm^2	-9.11 mm	$4.63\ 10^{-2}$ mm^2	-9.12 mm	$2.78\ 10^{-2}$ mm^2
4	29.5 s	32.9 s	-2.5 mm	$1.56\ 10^{-3}$ mm^2	0.56 mm	$9.56\ 10^{-4}$ mm^2	-12.98 mm	$1.68\ 10^{-6}$ mm^2
5	36.9 s	40.4 s	-7.4 mm	$8.73\ 10^{-4}$ mm^2	9.51 mm	$4.56\ 10^{-4}$ mm^2	-8.86 mm	$5.25\ 10^{-4}$ mm^2
6	45.1 s	48.1 s	-7.2 mm	$9.42\ 10^{-4}$ mm^2	-9.59 mm	$2.15\ 10^{-4}$ mm^2	-8.77 mm	$2.57\ 10^{-4}$ mm^2

Fig. 9. First Validation. All components are expressed in the local finger reference frame shown in Fig. 8(d)

owing to the small size of the object to be grasped and to the precision of the operation involved. The possibility of lifting a coin while wearing the device is an indication of how the device does not hinder performing nimble operations.

Finally, the fifth task involves lifting an egg (mass 58.3 grams). As previously discussed, a limitation of our device is that while wearing a subject is prevent any direct cutaneous feedback. It is thus interesting to see how precise force control can be. This is exactly the scope of this last task: lifting an egg without breaking it requires proper control of the forces applied by fingertips, and the fact that this task can be performed while wearing the device shows that it allows to retain a certain degree of precision.

The tasks described in this section were aimed to give a sample of the device versatility, and to show that despite the alteration of cutaneous feedback it is still possible to perform nimble tasks; deeper force analysis is demanded to future works.

C. Comparison with a sensorized object

In this section we perform a last experiment to compare readings from the wearable device with those coming from a trusted sensorized object, as a further validation. Fig. 11(a) shows the setup: an inverted T sensorized object, similar to the one used in [9], is lifted while wearing the device on two fingers. An unbalancing mass is placed on the left side of the object: the task requires to lift it while keeping it level, meaning that a compensatory moment needs to be applied to balance the effect of the weight. Contrarily to the work presented in [9], we are not interested in performing an analysis of learning, thus a bubble level is attached to the inverted T, in other to make the task trivial for the subject.

Fig. 11(b)- (d) show reconstruction of posture for a sample of time: in Fig. 11(b) the complete grasping setup is reconstructed, while Fig. 11(c) and Fig. 11(d) show posture and forces respectively for the wearable device and the sensorized object.

This task allows more detailed study and numerical comparison of forces. Quantities considered are force components tangential and normal to the object, and the compensatory moment required to contrast the action of the weight. Following the convention introduced in [9], we assume normal force to be positive when the fingers are pressing against the inverted T, tangential force to be positive when the object is lifted, and the compensatory moment to be positive when it contrasts the action of the mass. Measurements of these quantities are obtained from both devices, and compared by calculating the differences for total

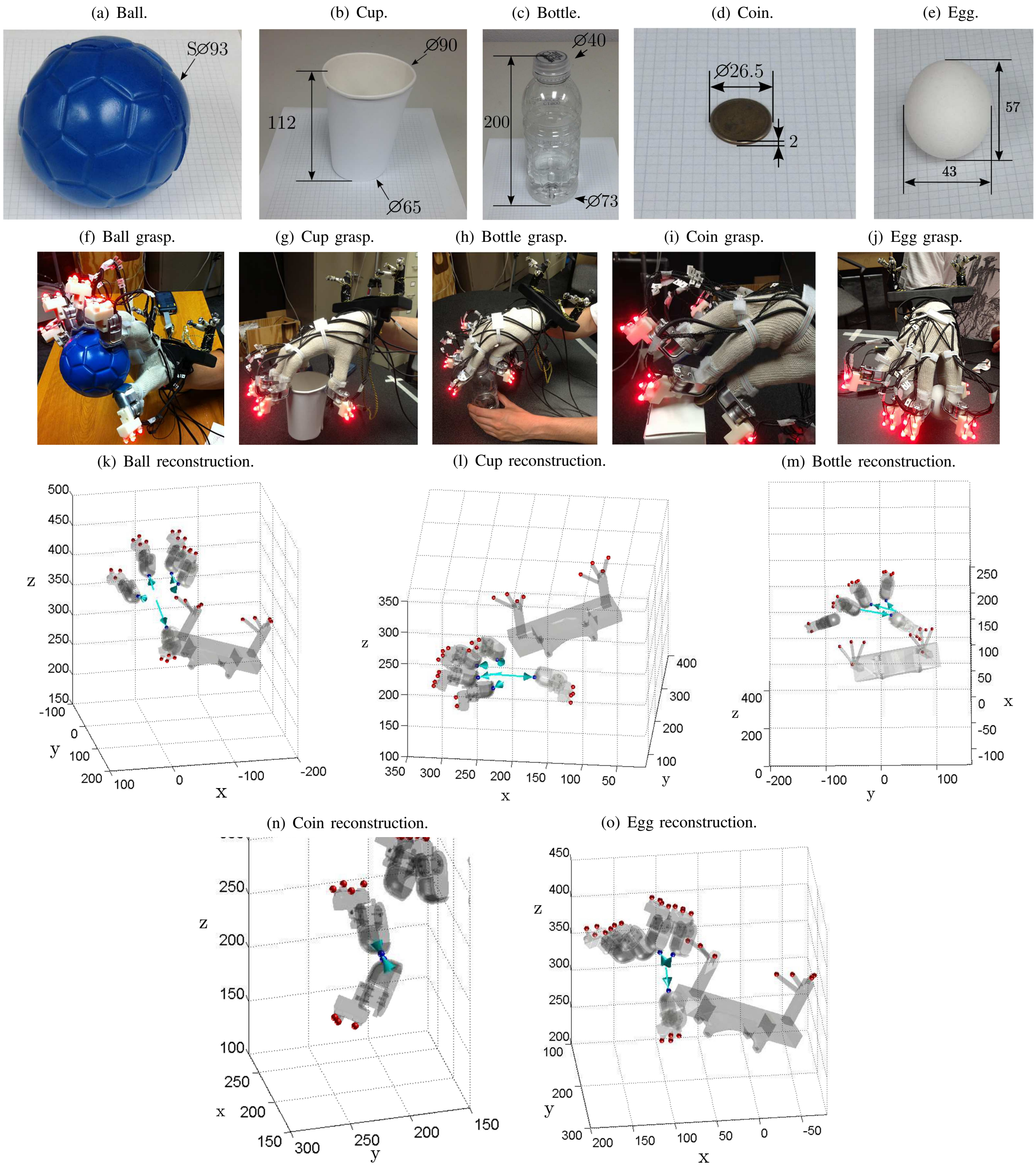


Fig. 10. Experimental Validation II: objects (panels a-e), task execution (panels f-j) and reconstruction (panels k-o).

(a) Grasping setup. (b) Reconstruction. (c) Forces on fingers. (d) Forces on object.

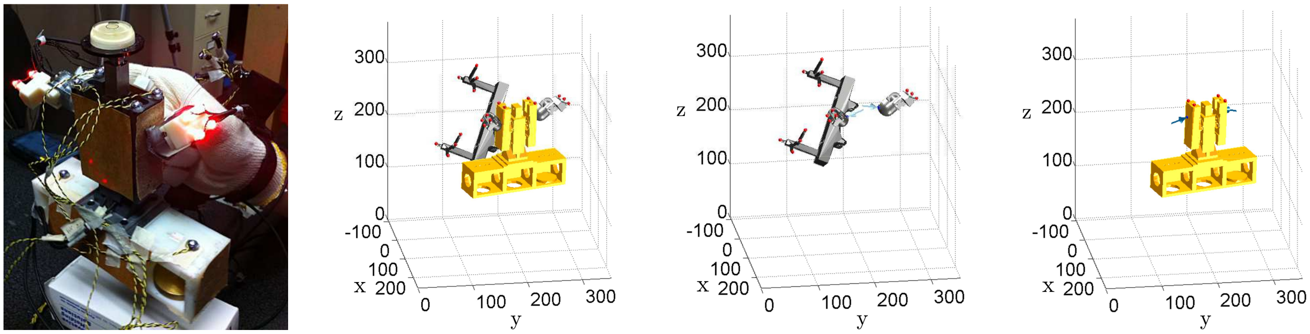
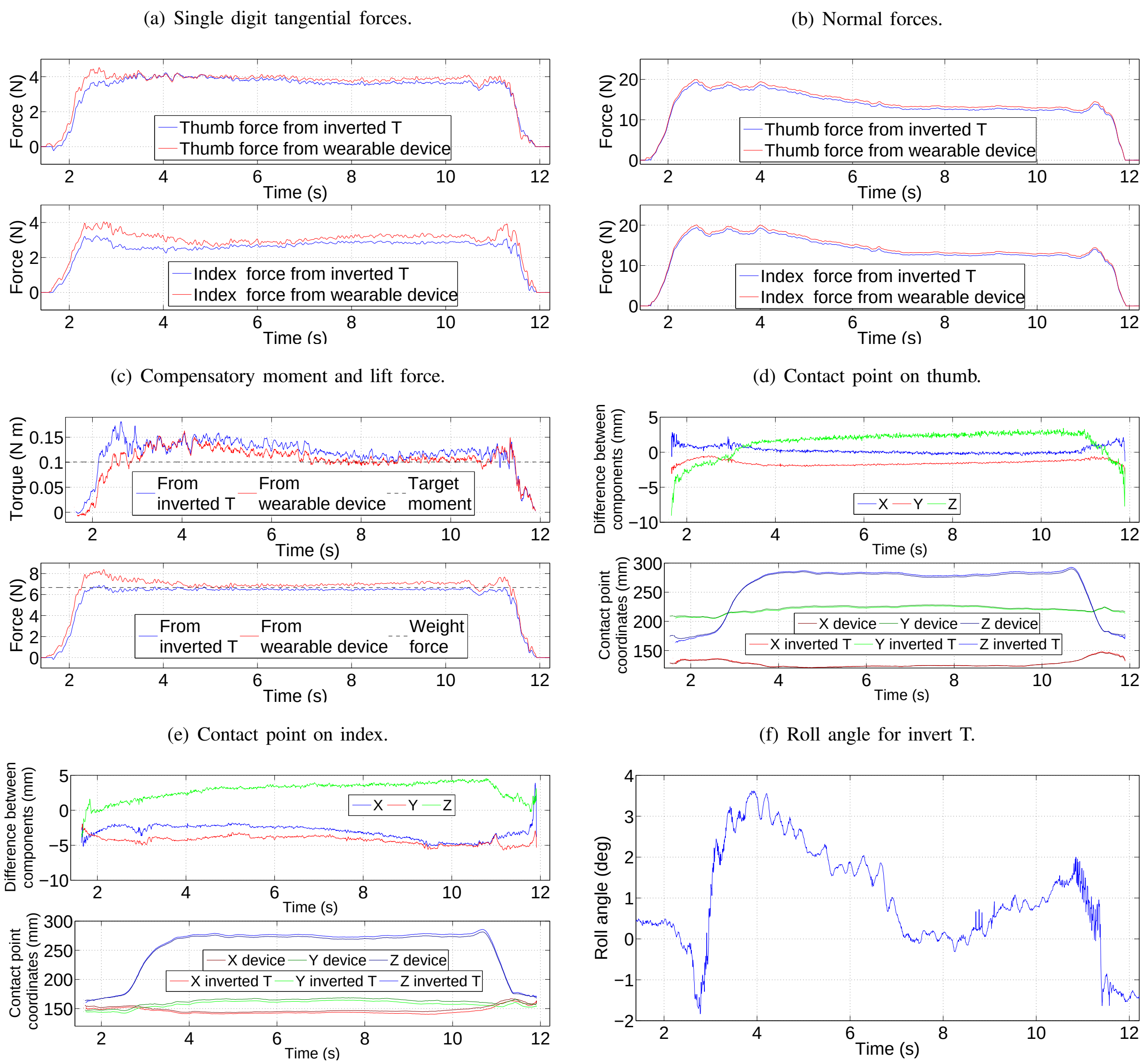


Fig. 11. Experimental Validation III: validation with sensorized object.



(g) Numerical data.

	ΔF_t	ΔM_c	Δc_x^T	Δc_y^T	Δc_z^T	Δc_x^I	Δc_y^I	Δc_z^I
Mean	0.58 N	12.67 N mm	0.28 mm	-1.50 mm	1.40 mm	-3.05 mm	-4.25 mm	2.84 mm
Variance	0.11 N^2	193 N^2 mm^2	0.33 mm ^{2}	0.14 mm^2	3.52 mm^2	1.07 mm^2	0.35 mm^2	1.63 mm^2
Maximum	1.71 N	38.12 N mm	9.73 mm	3.13 mm	10.65 mm	5.18 mm	5.68 mm	6.87 mm

Fig. 12. Force analysis.

tangential forces (ΔF_t), compensatory moments (ΔM_c) and contact point coordinates for thumb (Δc_x^T, Δc_y^T and Δc_z^T) and index (Δc_x^I, Δc_y^I and Δc_z^I).

Fig. 12 shows plots for these quantities. It can be seen in Fig. 12 (a)- (b) that, while normal forces are basically the same, there is a minor difference in values of tangential forces, which averages at around 0.5 N and decreases once a steady state is reached. This can be ascribed to the glove setup: while the presence of elastic bands helps keeping cables steady on the hand, it also potentially induces a distorting effect when the hand is moving and/or applying a force.

Fig. 12 (c) shows plots for compensatory moments and total tangential forces, comparing them with the moment caused by the side weight (100.5 N mm) and the force from the global weight of the object (6.67 N), respectively. The difference between values of tangential forces as measured from the thimbles and the inverted T also causes a small difference between the compensatory moments.

Moreover, Fig. 12 (d)-(e) show that, as a consequence of differences in forces, contact point coordinates also have differences of components (a few millimeters).

To provide a better understanding of the task development Fig. 12 (f) shows the roll angle of the invert T, which is an indication of how successful the task was. In can be seen that the inclination stays fairly low: it is in fact barely distinguishable from the slight inclination of the table where the object is standing at the beginning of the task. Differences are better quantified in Fig. 12 (g).

VII. Conclusions

This paper presented the design and implementation of the *ThimbleSense*, a wearable device that allows to obtain measurements of forces applied during grasping and to estimate the position of the contact points over their external surface. By combining it with a motion capture system we have also been able to integrate force measurements with position and orientation estimation which, in turn, allows to express forces and contact point components in absolute reference frames. Five *ThimbleSense* with their absolute localization system are integrated through use of a fabric glove and tested experimentally.

Experimental validations qualitatively show the accuracy in estimating the contact point (VI-A) and the position and orientation of fingertips (VI-B). To achieve a more quantitative comparison with a reliable reference, a validation with a sensorized object has also been performed (VI-C). Results from this last validation show small differences between the wearable device measurements and the sensorized object readings, which can be ascribed to the glove setup.

Owing to the versatility in being able to measure forces and fingertips position and orientation during grasping of variously shaped objects, we believe that this device shows promise to be a powerful tool in studying human hand behaviour.Ongoing work will involve performing a more thorough validation, by trying to reproduce results obtained in previous publications with sensorized objects. Moreover, some room for improvement is left on the design of the device, especially on the design of a localization setup less cumbersome respect to the adopted to motion capture systems, and a setup which provides a more stable support than the fabric glove with elastic bands we used here.

VIII. Acknowledgments

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