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

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***Abstract*— Measuring contact forces, applied by a hand to a grasped object, is a necessary step to understand the misteries that still hide in the unparalleled human grasping ability. Nevertheless, simultanous collection of information about the position of contacts, and about the magnitude and direction of forces, is still an elusive task when it comes to the reduced dimension of hands.**

In this paper we introduce a wearable device that faces this problem. It can be used to measure generalized forces during grasping. By assembling a pair of supports around a commercial 6 axis force/torque sensor, we obtain a thimble that can be easily positioned on fingertips. 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 needing for any assumptions on the kinematics of the hand. Finally, use of the contact centroid algorithm, introduced in [1], allows to determine position of the contact points during grasping.

Desing and implementation of the device are shown, as well as some preliminary experimental validation.

I. Introduction

The human hand has a complicated structure, with joints allowing for a high number of degrees of freedom. Despite this underlying complexity, experimental evidence suggested through the years that, in 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 neuromuscolar system [4]. Synergies have an immediate and practical application in the construction of robotic hands, since allow 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], the more basic, as in [3], compel grasping from pre-determined locations, while the more sophisticated, as in [9], allow being grasped in more generic configurations, even if sometimes this 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 favour versatility: this can be accomplished by using gloves and pressure sensors which, however, do not provide any information regarding shear forces. There exist more advanced approaches that allow measuring shear forces: an example is the setup using fingernail sensors introduced in [10]. However, this method requires fine calibration to correlate blood distribution under the finger nail with forces, and gives 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, allowing to measure all components of both forces and torques applied upon grasped objects. This is achieved by combining a commercial six axis force/torque sensor with a pair of support shells, which as a matter of fact blends the two 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 way to measure position. Owing to the fact that torque measurements are available, by using the algorithm proposed in [1], it is possible to determine the position on the thimble of the center of contact with the object being touched. Combination of all these information allows for

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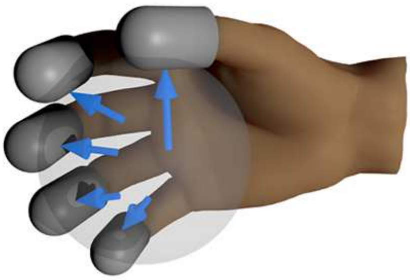


Fig. 1. Concept of the *ThimbleSense* digit-wearable tactile sensor.

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

Fig. 2. The *ThimbleSense* wearable force/torque measuring device, used on the distal phalanges of the DLR Hand II.

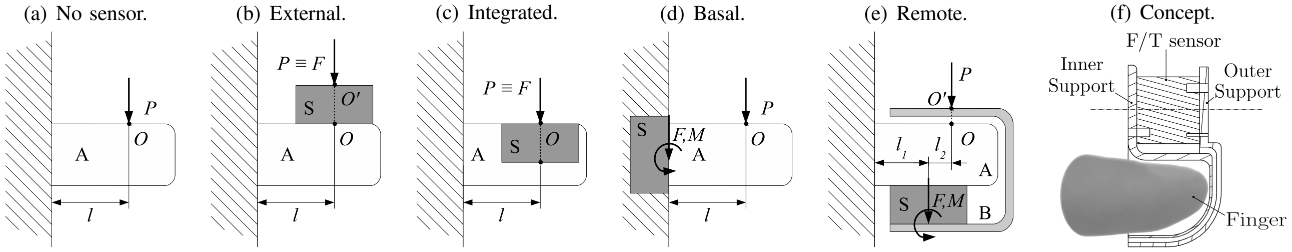


Fig. 3. A basic loaded structure (a), possible ways to sense the load (b-e), and the concept behind our shell-based wearable design (f).

full reconstruction of the 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. Consider the simple 2D example shown in Fig. 3(a), where a rigid body **A**, attached to a frame, withstands a force P applied on point O perpendicularly with respect to its main axis at position l. Suppose that a sensor **S** is available which is able to measure force F and torque M applied on its surface is available. The simplest course of action to measure the applied force consists in interjecting the sensor between the applied force and the object **A**, as in fig. 3(b). This solution, which is in general possible only when the position l where the force is applied is *a-priori* known, has the disavantage of dislocating the position in which the force P is applied from the original position O to the remote position O'. This displacement can sometimes be recovered (as in fig. 3(c)), by excavating a hole inside object **A**, where to integrate the sensor.

Another possibility to sense the load P consists, as in fig. 3(d), in splitting the structure in two parts, separating body **A** from the frame, interposing the the sensor between them. This allows, 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.

The three approaches exposed so far lead the design of common sensorized objects, but they can not directly be applied to a human finger, and also considering a robotic finger, their application would require integration from the early stages of the hand design. The motivation behind this is that approaches (c) and (d) are invasive with respect to the finger, while approach (b) is invasive with respect to the grasp itself, because typical dimensions of force/torque sensors are not negligible with respect to those of the hand.

To equip a finger with a sensor capable of results similar to thoese which can be obtained with approach (d) (simultaneous reconstruction of force and contact position), without compelling the contact to happen on the small surface of the sensor, poses a technological question. Fig. 3(e) shows a possible solution to this problem: by attaching the sensor **S** to object **A** on one side and to a properly designed shell **B**, it is possible to take advantage of the non-invasiveness of solution (b), and of the ability to reconstruct the contact position of solution (d). It can be noticed that, as in solution (b), the load is not directly applied on point O but on O', however, contrarily to solution (d), a proper design of shell **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). Next sections shows how this concept is transformed into a design and realized.

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. Thanks to this a complete measurement of forces and torques can be obtained. Since geometry of the external support is known, it is also possible to obtain the position of the contact centroid of the loading force P, resorting to 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 finger and external surface of the outer shell must be as thin as possible, while being able to keep the outer shell separated from the inner shell when load is applied.
- *Weight*: the device needs to be light, to minimize the effort necessary to move the device itself. 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.

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.

IV. Mechanical Design

To finalize the mechanical design of the *ThimbleSense* shells, the ATI nano 17 six axis F/T sensor [11] was selected.

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

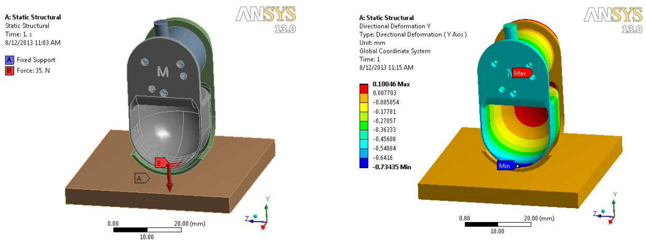


Fig. 4. FEM analysis: load on the inner shell.

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

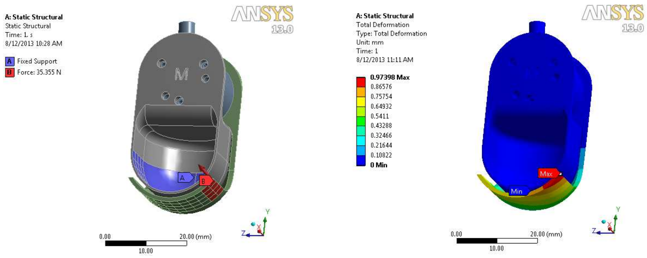
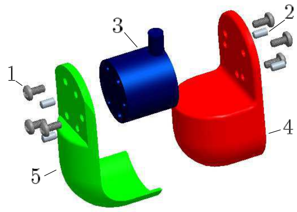


Fig. 5. FEM analysis: load with lateral component on the outer shell.

(a) CAD model (exploded view).



(b) Components.

Number	Name
1	Screw m2x4
2	Dowel pin 2x4
3	ATI Nano 17
4	Inner shell
5	Outer shell

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

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

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 with a high precision scale, reasonable bounds of the forces applied by a finger were estimated. An average value for the force was found to be 10 N, while 35 N appeared as a superior limit, achieved only when trying to press much force as to render the application of further pressure unconfortable. In an attempt to be conservative, loads on the structure were modelled as localized forces applied on the bottom of the open ends of either the inner and the outer shell.

A custom material has been defined for sensor mechanical properties, with elastic modulus coherent with those described by the data sheet. In the model shown both shells and the gap are 1 mm thick. 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 lesser than 1 mm. Since the load model chosen is by far an overestimation of the actual load, this design 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.

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*.

Grasping objects with a smooth, metal thimble is not an easy task due to the scarse friction. To facilitate the task, a friction surface was applied to the outher 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 is visible 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). Elastics are added to keep the structure stable. This component makes the device actually wearable, it is used to interface hand and thimbles in the experiments which we introduce in the following sections.

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 them in a global reference frame we need a way to obtain position and orientation of the thimbles.

Position and orientation of a rigid body can be estimated from the position of a number of points attached to it [13].

Coordinates of points attached to the thimble can be obtained, for example by using the 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 [14], and designed and realized suitable ABS plastic supports to attach the led beacons to the thimbles.

(a) CAD model.

(b) Physical realization.

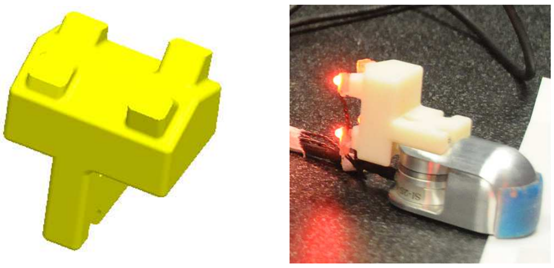


Fig. 8. ABS support for Phase Space markers.

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 lose track of one marker during the 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. In the following sections some preliminary experiments make use of the full capabilities of our device.

VI. Experimental Validation I

In this first experiment, a first validation of the device is performed to test 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. 8(a). The thimble is then placed on a finger, which lays on a fixed support (Fig. 8(b)): the points are pressed with a sharp tool (a pen), in the order shown in Fig. 8(a). The measurements are read during the task through a LabVIEW VI, which allows to obtain a sampling rate of 1 KHz.

In Fig. 9 the results of this experiment are shown. Fig. 8(c) shows contact points with forces and torques applied for six samples of time, one for each target. Fig. 8(e), 8(f) and 8(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 $\{F\}$.

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.

VII. Experimental Validation II

This second experiment shows a qualitative reconstruction of postures of the thimbles and of applied forces For this purpose, during the execution of five tasks, defined involving objects with different shapes, and different degrees of challenge for the device.

Fig. 10 shows the objects used for the five tasks, as well as the task execution and the reconstruction of the contact configuration (forces and contact points). Please refer to it 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 requires lifting a soft paper cup partially filled with water (weight 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 (weight 251.3 grams). The degree of challenge here is substantially higher, since a nimbler movement needs to be performed to open the bottle compared to the first two tasks. 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 requires to lift a one dollar coin (weight 8 grams) placed on a small support. This task is a challenging one, owing to the small size of the object to be grasped and 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 (weight 58.3 grams). Since there is no cutaneous sensation available while wearing the glove, it is interesting to see how precise force control can be. This is exactly the scope of this task: lifting an egg without breaking it requires proper control of the forces applied by fingertips, the fact that this task can be performed while wearing the device shows that it allows to retain a certain degree of precision.

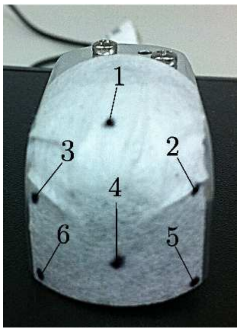
The tasks described in this section were aimed to give a sample of the device versatility, deeper force analysis is demanded to future works.

VIII. Experimental Validation III

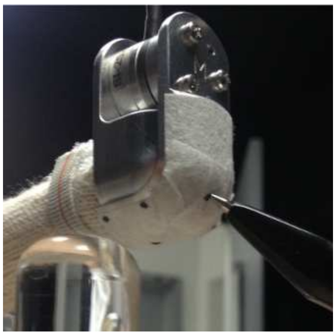
In this section we perform a last experiment to compare readings from the wearable device with those coming from a trusted sensorized object, as a further validation of the proposed device.

The setup is shown in Fig. 10(a): an inverted T 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 was attached to the inverted T, in other to make the task trivial for the subject.

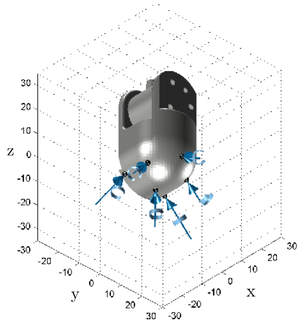
(a) Sensor with marks.



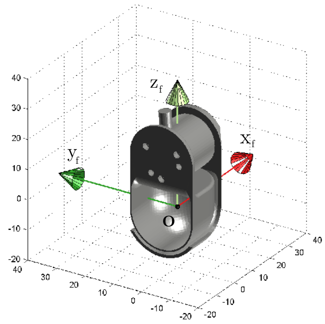
(b) Setup for validation I.



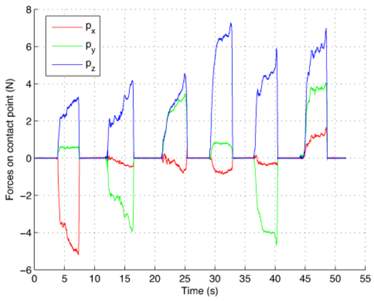
(c) Reconstruction of loads.



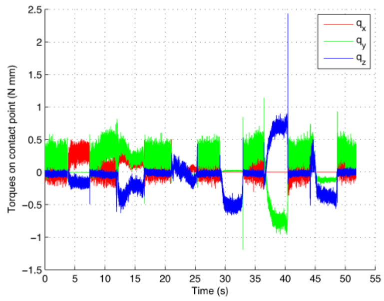
(d) Local finger coordinates {F}.



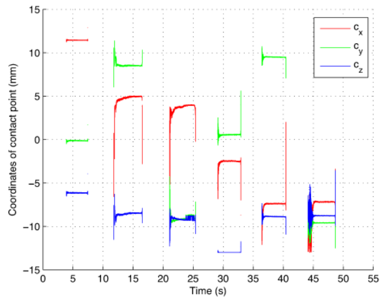
(e) Forces on contact point.



(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)

Fig. 10(b)- 10(d) show reconstruction of posture for a sample of time: in Fig. 10(b) the complete grasping setup is reconstructed, while Fig. 10(c) and Fig. 10(d) show posture and forces respectively for the wearable device and the sensorized object.

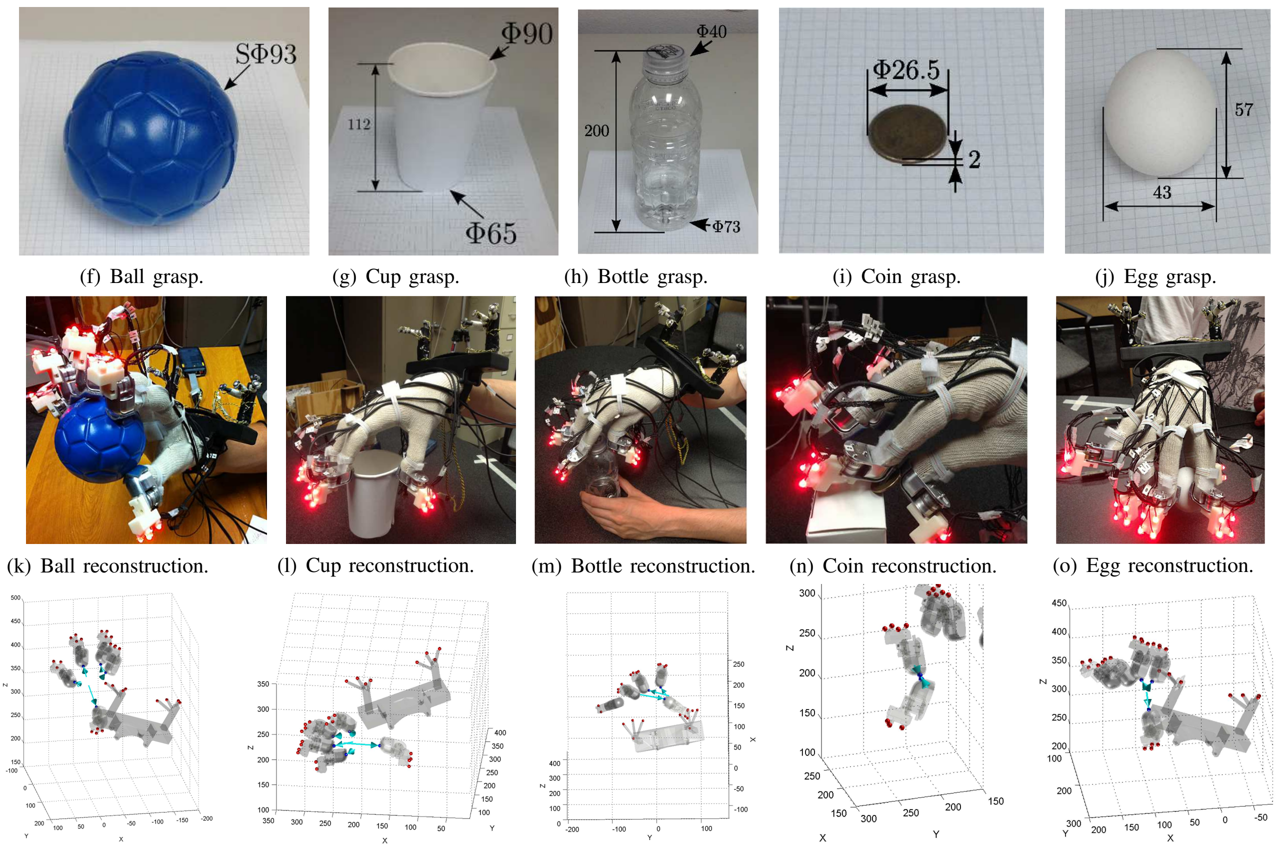
This task allows more detailed study and numerical comparison of forces. Quantities considered are force components tangential and normal to the object, and the compensatory moment required to contrast the action of the weight. Following the convention introduced in [9], we assume normal force to be 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 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).

In Fig. 12 plots for these quantities are shown. 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 elastics 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 respectively 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). The difference between values of tangential forces as measured from thimbles and inverted T also causes a small difference between the compensatory moments.

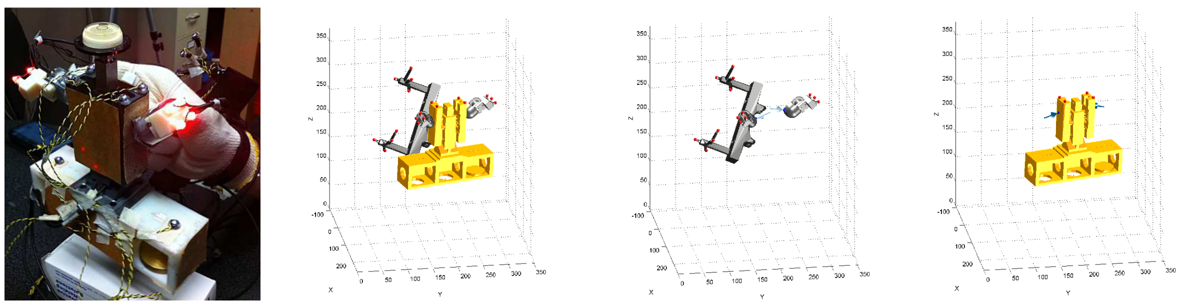
Moreover, Fig. 12 (d)- 12 (e) show that, as a consequence of differences in forces, contact point coordinates also have differences of components (a few millimeters).

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



(a) Ball. (b) Cup. (c) Bottle. (d) Coin. (e) Egg.
(f) Ball grasp. (g) Cup grasp. (h) Bottle grasp. (i) Coin grasp. (j) Egg grasp.
(k) Ball reconstruction. (l) Cup reconstruction. (m) Bottle reconstruction. (n) Coin reconstruction. (o) Egg reconstruction.

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



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

Fig. 11. Validation with sensorized object.

the object is standing at the beginning of the task. Differences are better quantified in Fig. 12 (g).

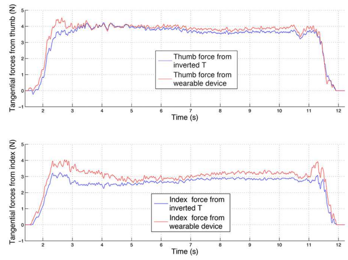
IX. Conclusions

We 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 join force measurements with a 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.

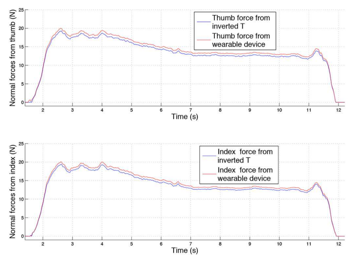
Experimental validations qualitatively show the accuracy in estimating the contact point (VI) and the position and orientation of fingertips (VII). To achieve a more quantitative comparison with a reliable reference, a validation with a sensorized object has also been performed (VIII). Results from this 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

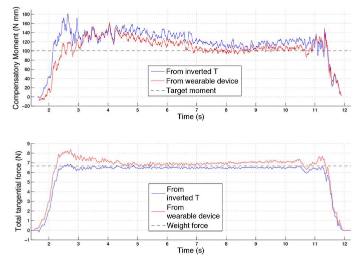
(a) Single digit tangential forces.



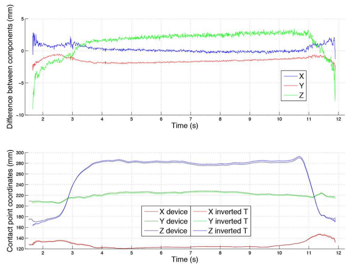
(b) Normal forces.



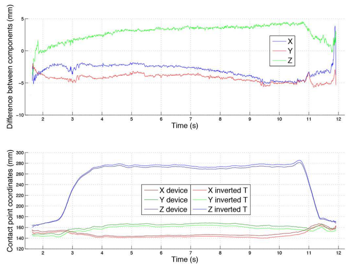
(c) Compensatory moment and lift force.



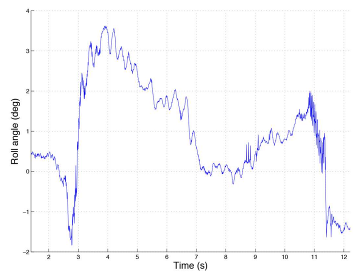
(d) Contact point on thumb.



(e) Contact point on index.



(f) Roll angle for invert T.



(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.

behaviour. Future 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, expecially on the design of a localization setup less cumbersom of the adopted to motion capture systems, and a setup which provides a more stable suport than the fabric glove with elastic bands we used here.

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