



DeTOP

Dexterous Transradial Osseointegrated
Prosthesis with neural control
and sensory feedback

Grant Agreement number: 687905

Topic identifier: ICT-24-2015

Start date of project: 01/03/2016

Duration: 48 months

Project website: www.detop-project.eu

D2.9

REPORT ON SENSORY SYSTEM

Leader partner: SSSA
Due date of deliverable: 31/08/2017
Actual submission date: 03/10/2017

TYPE OF DELIVERABLE

R	Document, report (excluding the periodic and final reports)	X
DEM	Demonstrator, pilot, prototype, plan designs	
DEC	Websites, patents filing, press & media actions, videos, etc.	
OTHER	Software, technical diagram, etc.	

DISSEMINATION LEVEL OF DELIVERABLE

PU	Public, fully open, e.g. web	X
CO	Confidential, restricted under conditions set out in Model Grant Agreement	
CI	Classified, information as referred to in Commission Decision 2001/844/EC	

TABLE OF CONTENTS

1	Introduction.....	3
2	Design of the SHP sensory system	4
2.1	Past experience with sensors for artificial hands.....	4
2.1.1	The SMARTHAND sensory system.....	4
2.1.2	Past experiments on sensory feedback substitution and influences on the sensory system design.....	5
2.2	Commercial sensorized prosthetic hands.....	5
2.3	Sensory system layout.....	6
2.4	Exteroceptive sensory system.....	7
2.4.1	Design of the index/middle finger biaxial force sensor.....	7
2.4.2	Design review of the finger.....	8
2.4.3	Design of the pinned joints.....	9
2.4.4	Design of the sensor.....	9
2.5	Design of the thumb biaxial force sensor	11
2.5.1	Requirements.....	11
2.6	Proprioceptive sensory system	12
2.6.1	Position sensor	12
2.6.2	Current sensor	12
3	Conclusions and future work	12

1 INTRODUCTION

The development of a suitable artificial sensory system to be embedded into the prosthetic hand is a necessary step towards the development of a bi-directional hand prosthesis able to deliver useful sensory feedback to the amputee. This deliverable describes the activities related to the design of the sensory system of the Sensorized Hand Prosthesis (SHP). Briefly, during the first 10 months of this task, the working team focused its attention on defining the sensor distribution within the hand and the requirements for those sensors. The main requirement that led sensor design and integration was represented by the need of providing a robust system, able to be used in clinical settings and characterized by good reliability. For this reason, sensors requiring complex wiring or signal processing have been avoided. The sensor set chosen will be able to provide information regarding the grasp and load forces applied by the fingers, as well as position and speed of the active joints and the torque applied on them by the motors.

2 DESIGN OF THE SHP SENSORY SYSTEM

2.1 PAST EXPERIENCE WITH SENSORS FOR ARTIFICIAL HANDS

2.1.1 The SMARTHAND sensory system

The Biorobotics Institute has a long experience in the design and development of sensorized hands. In particular, during the SMARTHAND project we designed and developed a new, dexterous, sensorized artificial hand with intrinsic actuation. This was a self-contained, transradial prosthetic hand able to be fitted to subjects with a very distal amputation level [1]. This hand was meant to be used in clinical scenarios by amputees employing different types of interfaces, in order to investigate the effectiveness of more natural and intuitive control and feedback strategies. For the SMARTHAND project, three different types of sensory information were considered: **joint position, grasp force** and **tactile/pressure**. Three different sensors, based on different physical principles were then developed.

The developed joint angle sensor was based on the Hall effect and comprised an Hall effect sensor (SS495A, Honeywell Inc., Freeport, USA) that senses the magnetic field produced by permanent magnets (103MG5, Honeywell) located on a mechanical structure; both components (Hall effect sensor and magnets) were integrated in the finger joints, one facing the other at a distance d (Fig. 1-A). These sensors were necessary since the fingers of the SMARTHAND prototype are underactuated and thus the single information of the encoder in the motor driving the finger is not sufficient to retrieve the position of all joints. The main advantages of such a sensor are its small dimensions, high reliability, low power consumption and linear input-output characteristics. Moreover, there are no sliding parts, so the need for maintenance is low. The structure has been embedded in the finger joints in a manner that magnets and the Hall effect sensor are solidly fixed in the finger frames, and wires run along the neutral axis of the finger, reducing at a minimum the mechanical stresses due to the finger motion.

Cable tension sensors based on strain gauges were integrated in the fingertip, in series with the tendon used to actuate the finger itself. In this way it was possible to measure the force applied on the transmission cables of each finger. This information is related to the grip force applied by the hand, and such a design has the advantage of being sensitive on the whole finger. A micromechanical structure was fabricated as a cantilever elastically strained by the cable during flexion of the finger and, especially, during grasping (Fig. 1-B). Two silicon strain gauges were glued on the sensor cantilever: one is the sensing resistor, while the other is a dummy resistor used for temperature compensation. The acquisition circuit was a standard Wheatstone bridge where the signal was amplified by an instrumentation amplifier (INA156EA, Texas Instruments); the amplifier gain is fixed, whereas the offset is tuneable by means of a trimmer. The signal conditioning board, measuring 5.5mm x 14mm was directly placed on the finger structure along the neutral axis.

Optoelectronic tactile sensors, composed of a light emitter, a light receiver and a propagation channel were employed as localized force sensors. Such sensor was placed in a groove machined in the finger. A flexible circuit in Kapton® was used to support one light receiver (in the centre) and two emitters (Fig. 1-C), covered by a transparent, very soft silicone layer acting as a light propagation channel. This was covered by an opaque silicone layer. Within this configuration, if the propagation channel is deformed by means of an external pressure, the light intensity detected by the receiver changes proportionally to the magnitude of the pressure.

The experience gained during the several experiments conducted using the SMARTHAND prototype suggested that sensors requiring complex wiring or signal processing must be avoided if the necessity of providing a robust system is a must. Among the sensors developed and described above, the ones based on strain gauges were the most reliable and useful and thus selected to be used in the DeTOP SHP.

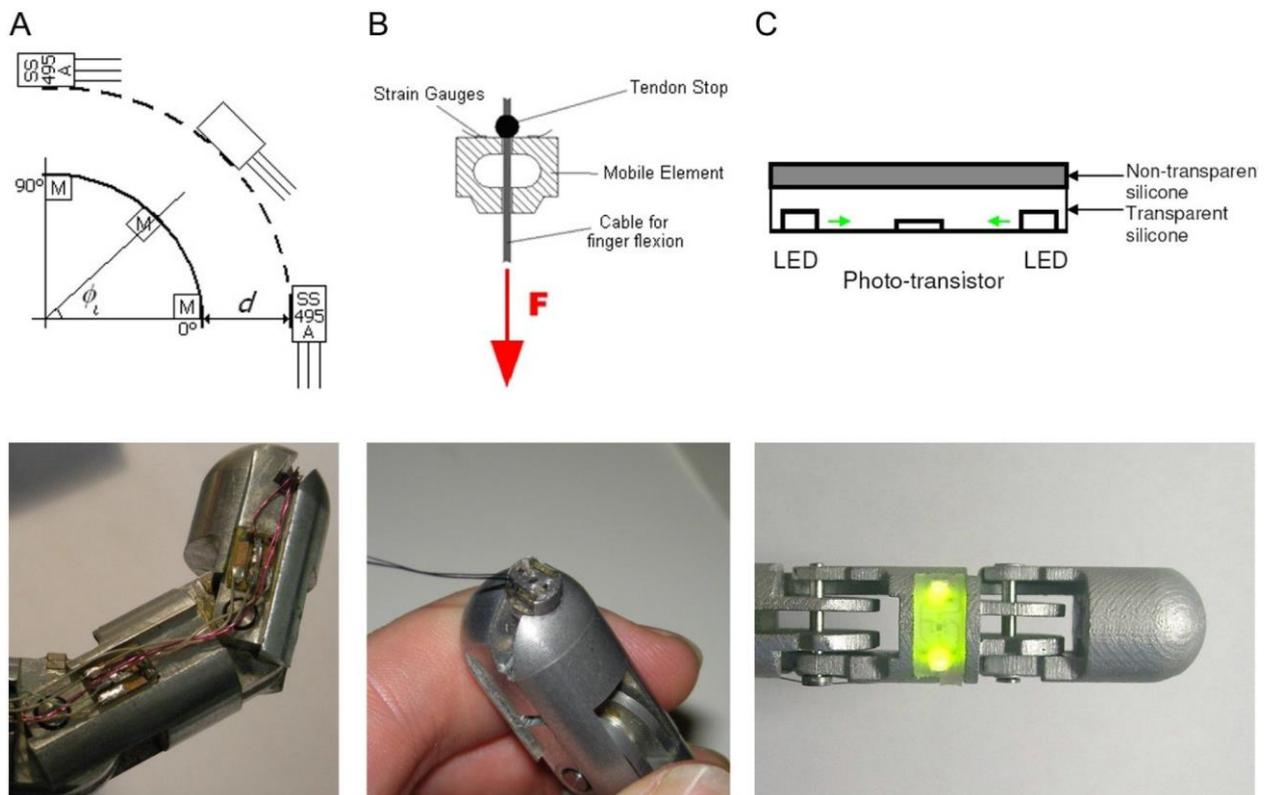


Fig. 1 Artificial sensory system of the SMARTHAND embedded in the finger. A) Position sensor based on the Hall effect. B) Cable tension sensor based on strain gauges. C) Tactile-pressure sensor based on light detection.

2.1.2 Past experiments on sensory feedback substitution and influences on the sensory system design

The SMARTHAND prototype was used in several pre-clinical case studies and experiments aimed at evaluating the best feedback strategies. In particular, our group explored a strategy that relies on temporally discrete sensory feedback that is technically simple to implement and provide the user with: the DESC policy. According to this neuroscientific hypothesis, motor tasks in humans are organised in phases delimited by means of sensory encoded discrete mechanical events [2]. In a typical pick and lift task, the key events are represented by *contact*, *lift-off*, *replace* and *release* of the object. Our group demonstrated that humans can integrate temporally discrete sensory feedback while controlling an artificial hand in healthy subjects [3] and for prosthetic control in daily life conditions [4]. To our knowledge, this was the first demonstration of a sensory feedback system that objectively and subjectively improved myoelectric prosthesis control beyond that observed with visual feedback alone in a realistic setup involving amputees.

These theoretical and experimental studies form a very strong evidence that a prosthetic hand sensory system should be able to measure the grasping force and the load force at the fingertip in order to be able to detect such key mechanical events and alert the user about them.

2.2 COMMERCIAL SENSORIZED PROSTHETIC HANDS

The work includes a brief review on the sensors used in prosthetic hands, restricting the analysis to the commercial devices. This information is extracted from the datasheets published by the manufacturers, and mainly describe the features enabled by the sensory system rather than on the technology used; yet they are still useful to set the requirements of the sensory system under development.

The *MyoHand VariPlus Speed* and the *SensorHand Speed* (manufactured by Ottobock HealthCare Deutschland GmbH) are the only commercial hands that take advantage of force sensors [5]. The first is equipped with a strain

gauge force sensor able to measure the grip force. The latter has an additional sensor within the fingertip of the thumb and is used to detect the slippage of a grasped object. The microprocessor of the hand senses when the object is about to slip and automatically increases the grip force until the object is stably grasped. In the *BeBionic Hand* (manufactured by Ottobock HealthCare Deutschland GmbH) [6] and the *I-Limb Ultra* (manufactured by Touch Bionics by Ossur) [7] the controller includes an Auto Grip feature that senses if a gripped item is slipping and automatically provides additional power to the motors in order to maintain a secure and safe hold. Similarly, the *Michelangelo Hand* (manufactured by Ottobock HealthCare Deutschland GmbH) [5] is equipped with a sensor in the thumb that detects friction caused by a slipping object and automatically tightens the grip to prevent slippage.

It is worth noting that these sensors are used just for allowing automatic control loops and are not intended for delivering afferent information to the user through an adequate user-prosthesis interface.

2.3 SENSORY SYSTEM LAYOUT

The SHP sensory system will be composed by two main parts: an **exteroceptive** and a **proprioceptive** sensory subsystem (Fig. 2).

The **exteroceptive** sensory subsystem monitors and measures the interactions between the grasped object and the hand and will be used to implement both low level and high level routines. The low level ones will implement automatic grasps or corrective actions in case of incipient slippage of a grasped object as for the commercial hand prostheses currently available (see Section 2.2). The high level ones will provide sensory information to the central control node which will in turn use those to deliver sensory feedback to the amputee. In particular, the exteroceptive subsystem comprises three force sensors able to measure the normal (i.e. the grasping force) and the tangential force (i.e. the load force) exerted by the fingers. Based on the previous experience, and on reliability issues, in accordance with PRE, SSSA chose to use strain gauge sensors. Six analog inputs are made available on the control board of the SHP for the acquisition of these force sensors. In order to improve the flexibility of the system, the current PCB layout supports both half and full Wheatstone bridge configurations. Albeit they require more space, full bridge configurations offer the advantage of automatically compensating for temperature drifts. This is important as it avoids changes in the reading from the sensors due to the heat generated by the motors during operation. Following the discussion of the Consortium during the general meeting in April 2017 we opted for mounting these three biaxial sensors on the index and middle fingers and the thumb of the SHP. This configuration will allow to measure the grasping and the load force for all the available grasps (i.e. cylindrical, bi-digital and lateral grasps).

The **proprioceptive sensors** will provide useful information about the hand kinematics and internal forces produced in the hand transmission, and will be mainly used by the low level routines of the hand. These sensors include: i) Hall effect sensors within the motors, ii) motor current sensors, and iii) mechanical limit switches embedded within each DoF transmission. Hence, the readouts from those sensors may be used to achieve position control, to limit the motor current absorption, preventing failures, and to limit the range of motion of the fingers.

The slave microcontroller of the SHP is used to compute the actual position and speed of the motors by sampling their internal Hall-effect sensors. This information is then passed to the master controller of the hand which implements the automatic control loops (Fig. 2). On the contrary, the motor current is calculated, by the master microcontroller, using the measure of the winding resistance. Finally, each active joint is equipped with two digital limit switches (A3213, Allegro MicroSystems Inc.) limiting the range of motion of the fingers.

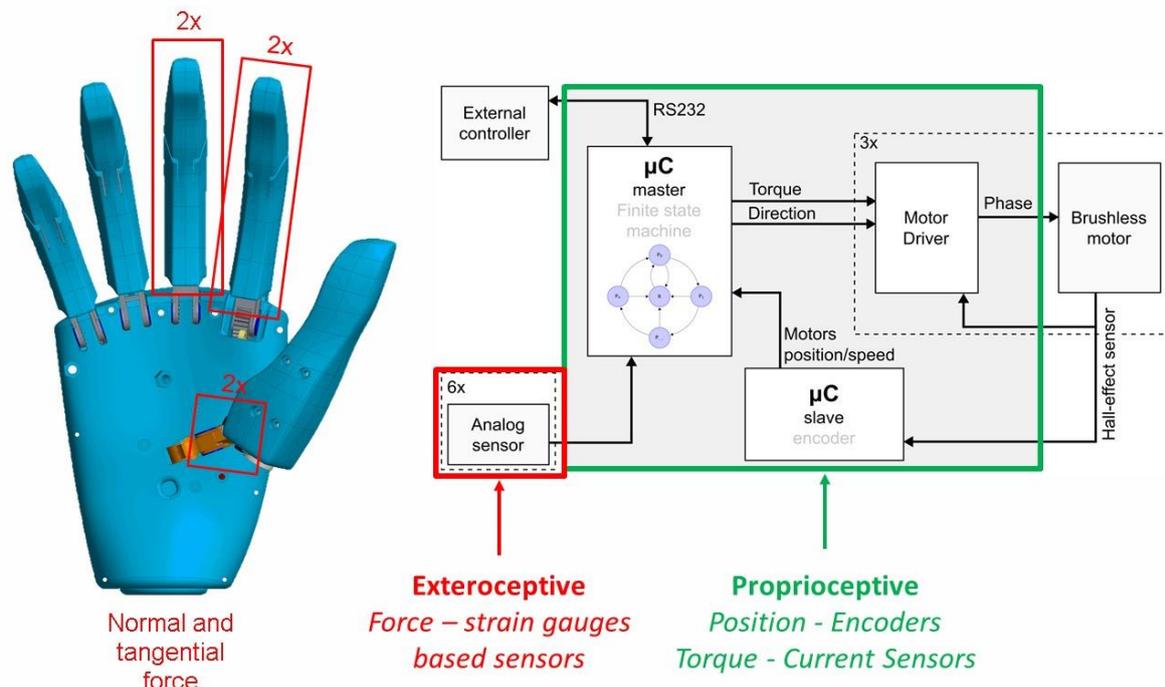


Fig. 2 Sensory system of the SHP. Left) Localization of the exteroceptive sensory system in the artificial hand; Right) Integration of the sensory system within the embedded controller of the SHP.

2.4 EXTEROCEPTIVE SENSORY SYSTEM

The exteroceptive sensory system will comprise three customized biaxial sensors mounted on the index, middle and thumb fingers of the SHP. The sensors embedded in the long fingers share the same design and will be embedded within the proximal phalanx of those fingers; the sensor in the thumb has a different design and the sensing elements will be integrated within the Geneva wheel at the based of the thumb.

2.4.1 Design of the index/middle finger biaxial force sensor

2.4.1.1 Requirements

The requirements for the set of sensors have been defined based on the previous experience (both in terms of sensors design and on the research related to the DESC policy) and based on the discussion of the Consortium during the general meeting in April 2017. The target specifications for the sensing elements to be embedded within the index/middle fingers are reported in Table 1. The range of sensitivity for both axes was set based on the expected performance of the hand and constrained by the limited size available within the fingers. Considering that the long fingers are opposed to the thumb during the execution of the cylindrical grasp (during this grasp the maximum grip force is usually required), and thus the force generated by the thumb is shared on multiple long fingers, we considered satisfactory a range of measure of 75% the maximum grasping force of the SHP. This, accordingly to Deliverable D2.1, is 60N and thus leads to a maximum measurable grip force of 45N. Similar considerations were drawn. When an object is lifted by the hand (in cylindrical and bi-digital grasps), its weight is partially supported by the thumb and partially supported by the long fingers (since they are opposed). For this reason we considered satisfactory a range of measure of $\pm 25\text{N}$ which correspond to a weight lifted by the hand of approx. 5 Kg.

Table 1 Target specifications for the biaxial load cell (index/middle fingers)

	Normal (Grasping) Force	Tangential (Load) Force
Measurement range	0 to 45 N	-25 to +25 N
Overload	200% FSO	

Linearity	$\pm 0.2\%$ FSO
Operating Temperature	-30°C to $+50^{\circ}\text{C}$
Bridge configuration	Full Bridge

2.4.2 Design review of the finger

The original design of the long fingers has been revised in order to increase the space available for the sensor. In particular, the finger presented during the first review meeting was designed with two joints each: a proximal joint (equivalent to the metacarpo-phalangeal – MCP – joint in the human hand) and a more distal one, here referred to as inter-phalangeal (IP) joint. The MCP joint was actuated by the motor, while the IP joint was passively linked to the MCP. The transmission used to transmit the motion from the MCP joint to the IP joint was based on an inverse four-bar linkage. The linkages of this transmission were placed in the middle of the proximal phalanx (Fig. 3-A). This wouldn't have left enough space for the integration of the load cell. For this reason, the architecture of the long fingers was re-designed, removing the four-bar linkage. This allowed to free space in the proximal phalanx without increasing the overall dimensions of the finger with respect to the previous design.

As a result the new long fingers design consists of a single segment actuated only at the level of the MCP joint (Fig. 3-B). The inverse four-bar mechanism was replaced by a compliant IP joint, with a Range of Motion (RoM) of ± 5 deg, manufactured in PA2200 Nylon ($E=1650\text{MPa}$, $S_u= 48\text{MPa}$). The torsional stiffness of the compliant joint was dimensioned to be $K_{\text{link}}=3,3\text{Nm/rad}$ (corresponding to an elastic link thickness of 3mm, width of 10mm and length of 10mm). This means that the finger comes to a full extension when a 12N load is applied to the fingertip. The design includes two mechanical stops to prevent the failure of the compliant joint when larger loads are applied (Fig. 3-B). Both the torsional stiffness and the RoM of the joint will be tested (and eventually revised) once the first batch of sensors will become available. The load cell was mechanically coupled with the finger cover and the frame through two pinned joints (Fig. 3-B), acting as non-permanent joints which can be removed without damaging the joining components.

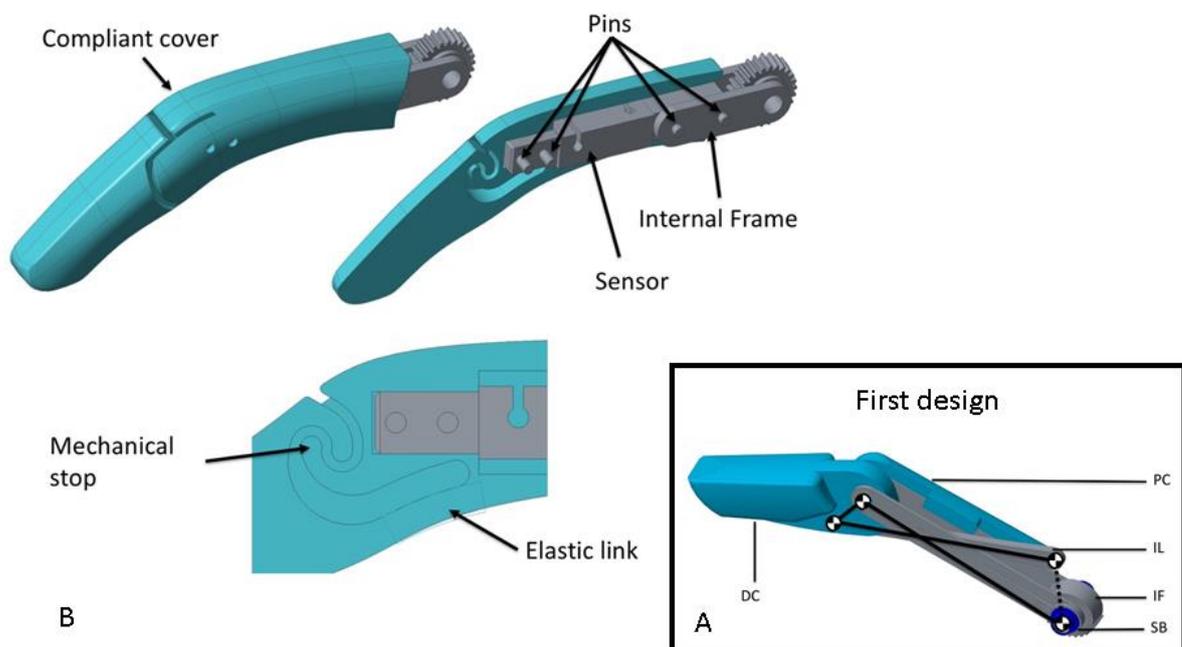


Fig. 3 Old (A) and new (B) design for the long fingers. In the new solution, the long finger consists of a single finger segment actuated at the MCP joint and with a compliant IP joint which allows a passive flexion/extension of ± 5 deg under load. The sensor is housed within the proximal phalanx and is connected to the cover of the finger and to frame by means of two pinned joints.

2.4.3 Design of the pinned joints

As stated above, the sensor is mechanically coupled with the finger and frame using pinned joints. Two pins for each side are fitted with interference between the two joining components and may be removed if necessary (for instance in case of replacement of the sensor). As for the sensors, the pinned joints were dimensioned based on the expected performance of the hand. In the proposed design, the loads are transferred from the cover of the finger to the sensor by means of the pins C and D, and then from the sensor to the internal frame by means of the pins A and B (**Errore. 'origine riferimento non è stata trovata.'**). The design was based on the stress produced by a force of 60N at the level of the pins A-B ensuring a safety factor of 2, while a safety factor of 3.5 was considered for the design of the two side plates of the internal frame. In this way, in case of overload of the fingers, the pins (which can be easily replaced) will fail before the plates.

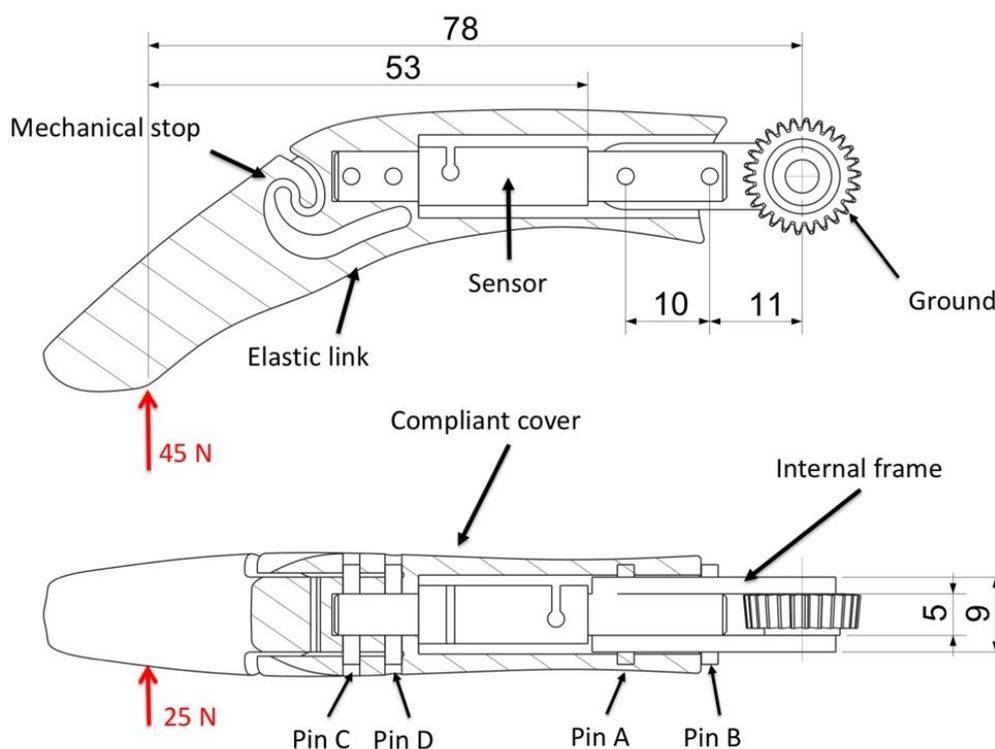


Fig. 4 Cross sections of the finger embedding the sensor. The figure shows the nominal loads applied at the fingertip used to design the pinned joints, the internal frame and the sensor.

2.4.4 Design of the sensor

The body of the force sensor has been designed and will be manufactured in collaboration with the company Strain Measurement Devices Ltd. (UK) in order to ensure high accuracy and reliability of the sensor due to their specialized manufacturing processes.

The force sensor is a steel beam designed to be placed on the proximal phalanx of the index and middle fingers (Fig. 5-A). The mechanical structure of this beam was designed in order to obtain a dual cantilever on which the strain gauges are applied to detect strains of both grasping and load forces. The 17-4 PH stainless steel (yielding strength $S_y=1100$ MPa, ultimate tensile strength $S_u=1300$ MPa) will be used to manufacture the mechanical structure of the sensor, while the thin film strain gauges (strain levels: 0-1200 μ strain [recommended], 3000 μ strain [maximum]) will be provided by Strain Measurement Devices Ltd. Finite Element Method (FEM) analyses were performed in order to verify the strain level in the sensing areas and the maximum stress both in the nominal condition (as reported in Fig. 4) and in case of overload (estimated as 2 times higher than the nominal condition).

Two analyses were performed (Ansys Multiphysics, ANSYS Inc., USA) for normal and tangential load conditions, respectively. The model of the sensor was meshed using 3D brick elements (109324 nodes and 63561 elements) and was constrained at the level of pins A-B. A remote force was applied through the distal pinned joint (pins C-D), as shown in Fig. 5-B.

Results (Fig. 5 and Fig. 6) shows that in proximity of the strain gauges' position, the strain values parallel to the cantilever axis at the nominal load condition are within the recommended range (600 μ strain and 1000 μ strain for the normal and tangential axis, respectively). In case of overload, the strain levels are lower than the maximum permitted value of 3000 μ strain (1300 and 2700 μ strain for the normal and tangential axis, respectively), while the maximum stress level (700 MPa) is lower than the yielding strength S_y of the material. These results confirm that, under the expected working conditions of the hand, the sensor deformation will never fall outside of the elastic range.

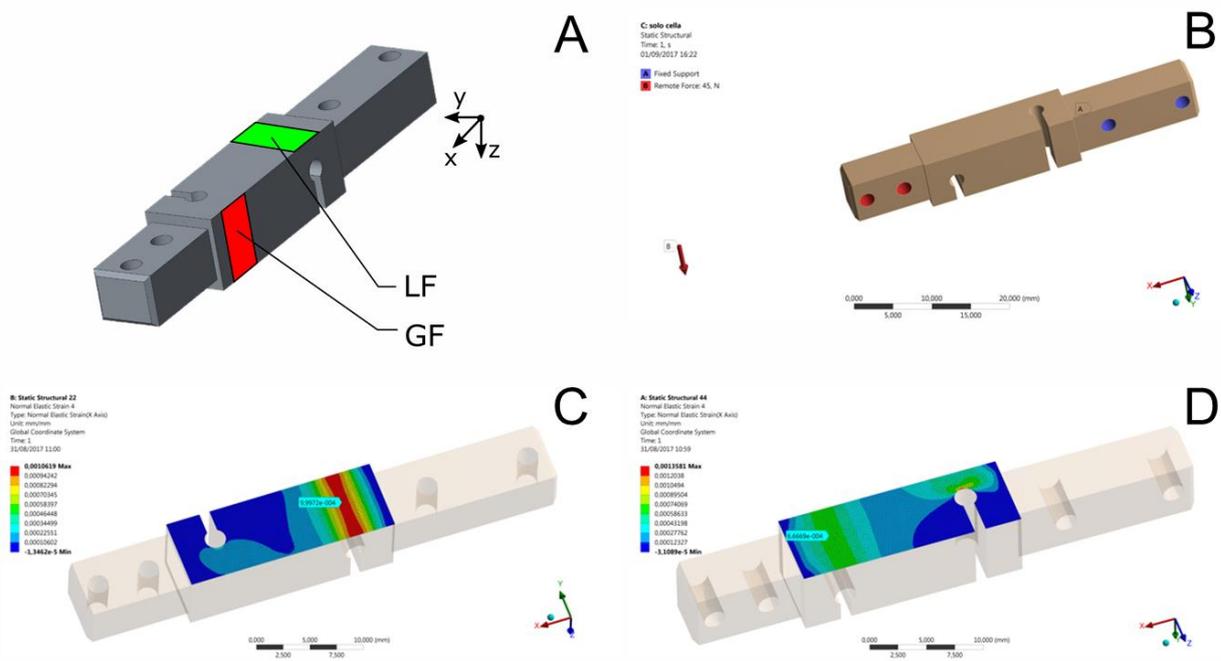


Fig. 5 Finite Elements Analysis of the sensor under nominal loads. A) Load cell body and localization of the strain gauges. B) The model of the sensor constrained through the pins A-B (blue) and under a remote load applied on the pins C-D. B-C) Strain resulting by the tangential (C) and normal (C) loads in correspondence of the strain gauges position.

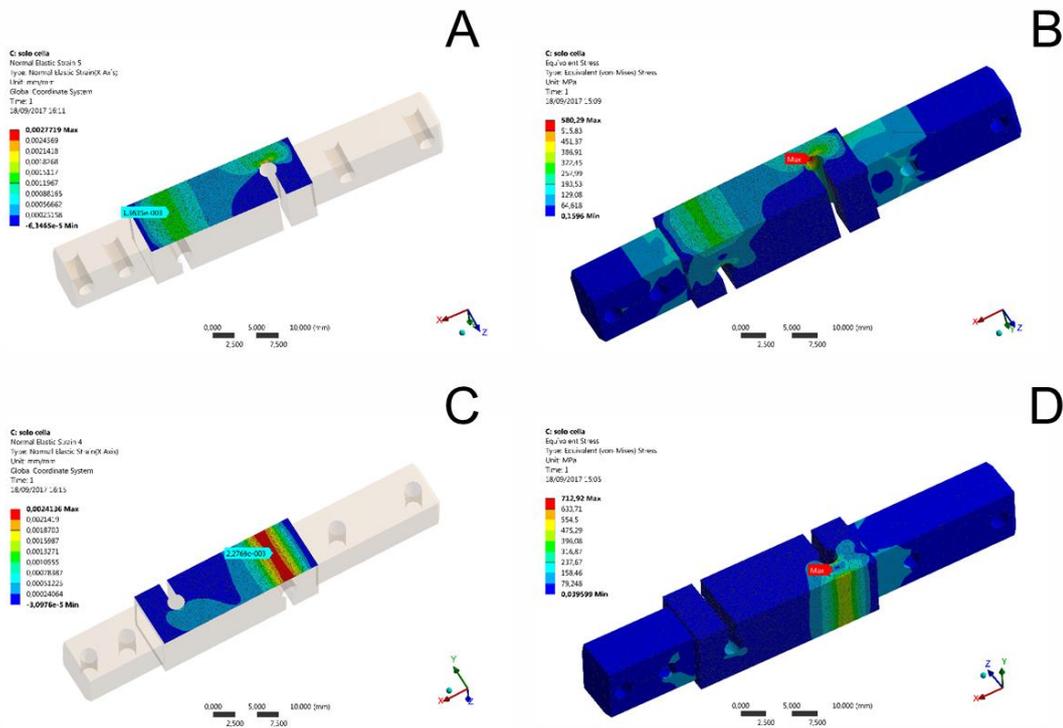


Figure 1

Fig. 6 Finite Elements Analysis of the sensor under overload. Strain and stress resulting by the normal (A-B) and tangential (C-D) overload in correspondence of the strain gauges positions.

2.5 DESIGN OF THE THUMB BIAXIAL FORCE SENSOR

2.5.1 Requirements

The target specifications for sensing elements to be embedded within the thumb are reported in Table 2. The range of sensitivity for both axes was set based on the expected performance of the hand considering that the thumb is always opposed to the long fingers and has to measure the maximum force exerted by the SHP, i.e. 60N.

As soon as the mechanical structure of the sensor will be designed (this activity is ongoing), its development will be carried out in collaboration with the company DELTATECH *Italy* (Italy), in order to ensure high accuracy and reliability of the manufacturing process.

Table 2 Target specifications for the biaxial load cell (thumb finger)

	Normal (Grasping) Force	Tangential (Load) Force
Measurement range	0 to 60 N	-30 to +30 N
Overload	200% FSO	400% FSO
Linearity	Under definition	
Operating Temperature	-30°C to +50°C	
Bridge configuration	Full Bridge	

2.6 PROPRIOCEPTIVE SENSORY SYSTEM

This section describes the proprioceptive sensory system of the SHP that will be used for implementing automatic control loops of the hand (such as position control, torque control, etc.).

2.6.1 Position sensor

The SHP hand is equipped with three brushless motors (EC10, Maxon Motor, Switzerland) which integrate Hall effect sensors that are exploited for position measurements. They provide information about the motion of the motor shaft, which the internal slave controller uses to extract information on its angular position. This information is made available as a *calibrated (or absolute) position*. This has an 8 bits resolution, ranging between 0 (finger completely extended) and 255 (finger completely flexed) for the thumb and for the last three fingers. For the transmission of the SHP that drives the semi-independent flexion/extension of the index and the adduction/abduction of the thumb, the position ranges between -127 (index completely flexed and thumb abducted) and 128 (index completely flexed and thumb adducted). The calibrated position resolution ranges between 0.4 and 0.7 deg depending on the finger.

2.6.2 Current sensor

The SHP integrates three motor current sensors (one for each degree of actuation, or DoA). The current sensors are obtained using current shunt resistors that are designed to monitor the current flow by measuring the voltage drop across a resistor placed in the current path. These sensors are housed in the main board of the hand. The motor current I_M is acquired through a 10 bits AD converter and is related with the output of the converter I_R through the following law:

$$I_M \approx I_R / 750$$

for all the DoAs (experimentally validated). The nominal motor current resolution is around 1.3mA.

The measurement of the motor current is linked to the torque generated by the motor through the torque constant. In addition to the measurement of the torque, these sensors will be exploited to automatically switch off the motors in case the current absorbed overcomes their thermal limit for a pre-defined amount of time, implementing a safety control loop.

3 CONCLUSIONS AND FUTURE WORK

This report describes the work done during the first 10 months of the task towards the development of the SHP sensory system. The SHP will be equipped with exteroceptive (biaxial force sensors based on strain gauges placed in the index and middle fingers and in the thumb) and proprioceptive sensors (monitoring the current absorbed by the motors and the position of the actuated joints) which will be used for implementing automatic control loops and, more interestingly, for delivering afferent information to the user through the OHMG-TR developed in WP3. The ongoing research activity is focusing on the development and manufacturing of the index/middle biaxial force sensor and on the design of the thumb biaxial force sensor. The first batch of sensors will be ready before March 2018, as planned within the DoW. As soon as the first prototypes will be ready, the sensors will be tested in order to guide the design of the second batch of sensors.

References

- [1] C. Cipriani, M. Controzzi, M. C. Carrozza. The SmartHand Transradial Prosthesis, *Journal of NeuroEngineering and Rehabilitation*, vol. 8, no.29, 2011;
- [2] R.S. Johansson, J.R. Flanagan, Coding and use of tactile signals from the fingertips in object manipulation tasks, *Nature Reviews Neuroscience* 10 (5), pp. 345-359, 2009;
- [3] C. Cipriani et al., Humans integrate discrete event sensory feedback in their sensorimotor control of a robotic hand, *Experimental brain research*, 232 (11), 3421-3429, 2014
- [4] F. Clemente, M. D'Alonzo, M. Controzzi, B.B. Edin, and C. Cipriani, Non-invasive, temporally discrete feedback of object contact and release improves grasp control of closed-loop myoelectric transradial prostheses, *IEEE Transactions on Neural Systems & Rehabilitation Engineering* (IF 2.583). Early access, on line Nov. 13 2015, Printed vol. 24, no. 12, pp. 1314-1322, Dec. 2016.
- [5] www.ottobock.com
- [6] <http://bebionic.com/>
- [7] <http://www.touchbionics.com>