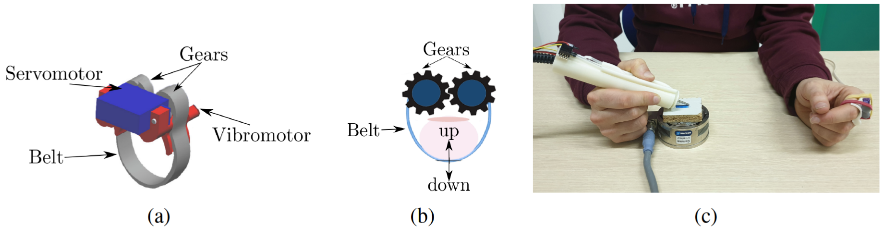


Figure 4.5: (a) Rendered 3D model of the device, (b) mechanism for pulling up/down the fabric belt, and (c) a user testing the proposed system.

are referred to [119] and [120] for further details on the force feedback generation. A manual calibration is performed for each participant to adjust the initial position of the belt.

The vibrational motor is placed horizontally alongside the device. It generates vibrations (1 g at 3.6 V) to notify the force threshold over-reaching.

4.3 Experimental validation

The experimental evaluation was carried out with a twofold aim: *i*) demonstrating the effectiveness of the haptic feedback in the aforementioned surgery and *ii*) identifying the best feedback approach. Ten users (six males, age 23-56, all right handed) took part in the experiment. One was a surgeon with many years of experience, three were medical students with five years of experience, while the remaining six were medical students with lower/no experience in performing open surgical procedures.

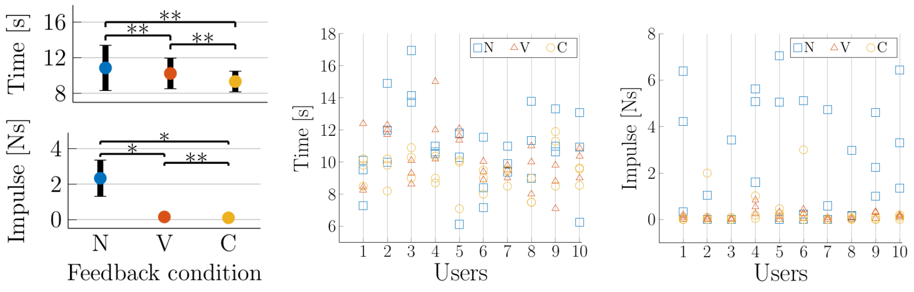
The experiment aimed at simulating a cochlear implant surgery. Participants were asked to completely remove a blue colored rectangle ($0.6{\times}2.0$ cm) from a piece of plywood using the instrumented drill (rotating at 15.000 rpm). Users wore the haptic ring on the left hand (see Fig. 4.5c), where a clear perception of the haptic feedback is allowed by the absence of vibrations. The main issue while performing a drilling task is that vibrations reduce the surgeon's sensitivity on the hand. Providing a haptic feedback (cutaneous, vibrotactile, etc.) on the same hand would not help the surgeon, which would not be able to clearly distinguish the stimuli.

Participants were told that the task was considered successfully accomplished when the drilling force was maintained in a specific range, i.e., [0–7.5] N, without overreaching the time limit of 13 s. The time limit has been introduced with two purposes: *i)* to prevent subjects from performing the task so slowly so as to completely remove the blue color being for sure under the force threshold; *ii)* to simulate as much as possible a real surgery, in which surgeons has to complete tasks within a time limit. However, participants were not asked to perform the task as fast as possible, but only to do it without overreaching the time limit.

For what concerns the force limit, a surgical task performed using a lower force implies an increase in control and safety. Indeed the starting point of the study is the hypothesis that the invasiveness of interventions might be reduced by adding haptic feedback to existing tools, in order to obtain a more controlled penetration in the bone. To test the capability of controlling the penetration, we selected a force threshold and asked the participants to complete the task without overreaching it, simulating a training exercise. If the exerted force is maintained under the threshold level, we can argue that the task is less invasive and thus safer. The limit value of 7.5 N has been chosen by performing preliminary tests on pieces of plywood, using the same setup of the experimental campaign. It represents the upper limit of a safety range in which the plywood is not in danger of breaking.

Three feedback conditions were evaluated: *i)* no feedback *(N)*; *ii)* vibratory alert in case of exceeding the force threshold *(V)*; *iii)* vibratory alert and cutaneous feedback proportional to the exerted force *(C)*. A proportional scale factor was used to map the measured maximum force into the admissible range of the ring. Each user performed a set of three trials per each feedback condition, resulting in a total of nine trials. The feedback modality for the three trials was organized in a pseudo-random order. Time to complete the task and impulse (the integral of the force out of the boundaries over the time interval) were considered as metrics for evaluating the task performance.

Before starting the experiments, participants were informed about the scale of the force. A familiarization period of 2 minutes was provided to acquaint participants with the system. In this phase, users tested the overreaching of the force limit with and without haptics, pushing the drill toward a piece of plywood until reaching the maximum value of force. First, a graphical indicator on a LCD screen displayed the contact force to the users and a led notified the reaching of the force limit. Then, participants wore the haptic ring and repeated the test perceiving the exerted force. In this case, the maximum value of force was notified by a vibration.



(a) (b) (c)

Figure 4.6: In (a) mean and 95% CI for all the feedback conditions are reported for time (upper panel) and impulse of the force over the threshold (lower panel). The p-values are reported on top of the error bars, $**$ and $*$ indicate $p > 0.05$ and $p < 0.0005$, respectively. In (b) and (c) users results for each trial are shown.

4.3.1 Results and discussion

Data collected in the experimental phase were analyzed by means of statistical tests. For each participant completion time and impulse were computed (see Figs. 4.6b and 4.6c).

All the participants were able to completely remove the blue color in the time limit of 13 s both with and without the haptic feedback. The average completion time among all the trials was 10.85±2.54 s, 10.23±1.72 s, 9.32±1.16 s for *N*, *V*, and *C* feedback conditions, respectively. Statistical analysis revealed that there is no statistically significant difference in the completion time of the task using different feedback and, as shown also in the upper panel of Fig. 4.6a, the task execution does not seem to be slowed down by the increasing number of stimuli to be focused on. This is a surprisingly positive result, which may lead to the following interpretations/conjectures: surgeons are not distracted or emotionally involved by the haptic device and do not perceive the haptic feedback as a noise or an annoying stimulus.

Since all the participants were successful in removing the blue color within the time limit, we can conclude that enough force was applied. However, the objective of the trial was to clear the blue rectangle without exceeding also the force limit of 7.5 N. In this regard, as a metric of success we considered the impulse of the force (N·s) over the threshold: the less is this value the better the experiment has been accomplished. Measures of impulse were used to compare performances: participants exceeded the force limit with 2.33±1.25 Ns, 0.15±0.16 Ns, 0.10±0.13 Ns testing the setup with *N*, *V*, and *C* feedback, respectively. Moreover, a one-way repeated measures ANOVA was conducted to determine whether there were statistically significant differences in impulse over the different feedback. There were no outliers and data were transformed using the squareroot transformation and passed the ShapiroWilk normality test ($p > 0.05$). The assumption of sphericity was violated, as assessed by Mauchly's test ($\chi^2(2) = 7.87$, $p < 0.05$). Therefore, a Greenhouse-Geisser correction was applied. The results of the test (reported in the lower panel of Fig. 4.6a) assessed that the feedback modality elicited statistically significant changes in over-applied forces ($p < 0.0005$). Post hoc analysis with Bonferroni adjustment revealed that the reduction of impulse was statistically significant: more in detail, the test revealed that there is statistically significant difference in performing the task with or without haptic feedback. In case of feedback, the impulse error had an almost complete reduction, which implies a more controlled penetration in the plywood. Compared with the absence of feedback, the impulse error had a mean reduction of 2.18 Ns (93.56%) and 2.23 Ns (95.70%) performing the task with *V* and *C* feedback modality, respectively. For what concerns the difference between the two haptic feedback, it is lower and not statistically significant. Using vibration and cutaneous feedback reduced in average the impulse of 0.049 Ns (32.66%) with respect to only vibration. In Fig 4.6a p-value, mean, and 95% Confidence Interval have been reported, both for completion time and exceeding impulse.

Supported by the outcomes of the statistical analysis, we can affirm that haptic feedback can enhance the safety in surgical hand-held drilling tasks, maintaining the drilling force in a specific range. In addition, participants to the experimental campaign reported positive qualitative feedback on the haptic-assisted experience and on the positioning of the ring in the contralateral side. They argued that the cover did not interfere with the task and it would be useful to introduce the device in real surgical procedures, after appropriate refinements.

For the sake of clarity, it is worth specifying that expert surgeons are surely able to understand which is the limit force to exert without the use of additional sensing devices. However, by means of our device this task can be simplified and the training period of young doctors can be shortened. The limit value of 7.5 N has been experimentally chosen and depends on the setup. Identifying a force threshold in real surgical procedures would be obviously much more complicated and require further experiments which need to be performed on real human bones. Indeed, the aim of the work presented in this chapter was to introduce just the proof of concept of a new device, testing its effectiveness in a simple drilling task which exemplifies the real case.

4.4 Conclusions

In this chapter, a novel approach to measure the force exerted on bones during drilling tasks in open surgery is presented. A pneumatic sensing cover for drills and a haptic ring to reproduce such forces were developed. The sensing cover is capable of measuring forces in the three directions of the space, but in the current design it is not capable of decoupling measurements along x-axis and y-axis. One pipe (i.e. *pipe z*) is in charge of measuring the forces along the z-axis, while two further pipes (i.e., *pipe xy1* and *pipe xy2*) are in charge of measuring the forces on the xy-plane. To properly reconstruct the force profile, we implemented both hardware and software filters. We tested our sensing device in a comparison with a high-resolution/accuracy commercial force sensor, demonstrating the robustness of our approach.

The advantage of our sensing system is that it can be easily adapted to any surgical drills, changing only few design parameters in the CAD model. Starting from the parametric design, it will be easy to adapt the cover to most of the available surgical drills of varying sizes and shapes. Given that otological drills have quite similar shapes, in most of the cases it may be sufficient to modify just the internal profile of the inner shell (e.g., introducing some shims), so as it is firmly attached to the drill, without changing the overall shape of the cover. For what concerns the size of the pneumatic cover, it was considered acceptable by the team of doctors which contributed in developing the device. The added weight of the cover (51 g) is so light that it has no influence on the surgical operation and also additional wiring is limited. However, we aimed at exploring these aspects in future works. Another advantage of the proposed solution is that the resolution and the range of our sensor are customizable: they can be modified changing the silicone pipes and the pressure sensors.

We evaluated the effectiveness of our haptic-assisted hand-held drill with long experience and novice surgeons. Forces and vibrations were exploited to help the users in evaluating the real exerted forces. We compared the performance of the participants with and without haptic feedback, proving that haptic enhancement outperformed the haptic-free technique. To evaluate the participants' performance, we decided to use the integral over the time of the force exceeding the threshold. A reduction of force such that the impulse over the threshold is approximately zero is a significant result, because it means that the haptic device helps the user in remaining always under the safety threshold.

This work demonstrated that our pneumatic system is a viable and reliable solution for drilling procedures in open surgery: exploiting a pneumatic method, the resulting device is the best compromise between reduced size and reliability of the force estimation. Compared to the pneumatic balloon, whose idea and refinement have been presented in Chapter 2 and Chapter 3, respectively, the great advantage of this sensing cover is that the operating phase and the force measurement phase can be executed at the same time. However, this solution can not be exploited in robotic surgery, due to the strict constraints on the size of the robotic instruments. It is also worth pointing out that the context of drilling procedures in open surgery poses challenges which are different from those faced in the previous chapters. In this case, the purpose of the haptic feedback is not to restore all the manipulation capabilities essentials to distinguish consistency of tissues and determine the occurrence of an abnormal mass, as in robotic surgery. When performing drilling tasks during open procedures, surgeons have direct access to the patient's body, but have no precise perception of the drilling force. Thus, in this case, the haptic display is used mainly to notify that the surgeon is reaching a force threshold.

In further developments, the cover can be instrumented with additional sensors (e.g. an accelerometer) to measure the inclination of the drill and improve the calibration procedure. During the initial calibration, in fact, two separate procedures were required to calibrate the two sensors because in the first prototype it is not possible to know the inclination of the drill and hence the exact distribution of forces on the pipes.

Chapter 5

Further applications of the pneumatic sensing in robotic manipulation tasks: an introduction

The work proposed in the first part of this thesis focuses on the challenges in force sensing raised by the medical framework, but it can be easily extended to more general scenarios. In the second part of the thesis, the concept of pneumatic sensing will be further extended until crossing the field of soft robotics for remote manipulation. The main contribution of the following chapters will be to present a viable solution to create smart environments exploiting soft technology that can be used by rigid grippers to perform more robust grasps and to provide safety and versatility.

Soft robotics is an emerging research field that takes inspiration from biological systems and exploits new materials and new manufacturing processes to build devices that are safe, robust, and suitable to operate in unstructured environments [121, 122]. Soft robots radically change the perspectives of design, mechanical modelling, and control. In particular, the field of soft robotics has greatly changed researchers' perspective on robotic grasping, introducing new hands and grippers [123, 124] that allow grasping and manipulation strategies that were inconceivable with rigid hands [125]. Differently from classical rigid robotic hands, soft hands can safely interact with constraints present in the environment that can be exploited for robust grasping performance, as shown in [125]. Thus, grasp planning with soft hands does not rely on exact models and precise positioning of contact points, but aims at using the direct physical interaction with the environment to constrain and grab the object (as in the example depicted in Fig. 5.1a) [126, 127]. This is not possible with rigid grippers (see Fig. 5.1b). Rigid robots, however, still have important features that are difficult to obtain with soft robots, such as the precision and repeatability of movements, as well as the possibility of having accurate measurements through sensors. The different features of soft and rigid hands make them suitable for distinct applications. Soft hands are more used in collaborative and assistive robotics [129, 130], while industrial picking still relies mainly on rigid grippers [131].

In Chapter 6, we propose a novel solution to take advantage of the strengths of both soft and rigid robotics approaches. We propose to use rigid robotic grippers while adding

(a) (b) (c)

Figure 5.1: (a) Soft hands, like the RBO Hand 2 [128], can easily interact with rigid surfaces for grasping objects. (b) Rigid grippers, instead, cannot safely exploit the environment. (c) A soft sensorized surface allows rigid grippers to exploit the environment to pick objects up and provides a grasp planner with information on object pose and weight distribution.

compliance to the surface laying beneath the objects to be grasped (see Fig. 5.1c). In other terms, we shift the focus from the gripper to the environment. This is achieved by introducing a grasping strategy that exploits the *SoftPad*, a matrix of silicone pneumatic modules connected to pressure sensors. When placed beneath an object during a grasping task, the SoftPad can be used to detect object pose, shape, and center of mass based on pressure variations inside the inflated modules. Given the estimated center of mass, a planner computes the center and the direction of grasp that can be used by a robotic gripper to pick the object up.

Thanks to the SoftPad, grasps can be performed without the need of a camera to locate the object and without prior knowledge on its mass distribution or its shape. Besides, the gripper can safely interact with the soft surface, coping with uncertainties on the object pose and achieving more robust grasps thanks to environmental constraints exploitation strategies [125, 127]. This approach goes beyond classical vision-based object detection strategies [132, 133], as it allows to estimate the center of mass of the object, not only its pose and shape. Besides, there is no need to add force sensors to the robot [126, 134], as the sensorized modules can detect the contact between the gripper and the SoftPad. Differently from the devices presented in the previous chapters, the SoftPad is not used for measuring interaction forces, but rather as a detector of object features and contact events.

In principle, combining an elastomeric layer with an array of tactile sensors could lead to a device comparable to the SoftPad. Indeed, having an elastomeric layer placed over a tactile array still brings the concept of adding compliance to the environment instead of the gripper. Nonetheless, we have preferred the fully pneumatic solution, that has several advantages with respect to other technologies. Even if there are many tactile sensors that can detect pressure distribution, we did not decide to go in that direction because the great advantage of having both the compliance and the sensing capabilities combined in the same customizable device is that the user can easily set several parameters depending on the objects to grasp, including modules size and material. The size (width, length, and thickness) of pneumatic modules is completely customizable. This feature is shared with other sensing technologies like soft sensors based on liquid metals or pressure sensitive conductive sheets (e.g., Velostat). However, their use still presents some challenges. In liquid metals sensors, none of the patterning methods is yet high-throughput, the interface between soft and hard materials within the device is still an issue, and studies should be performed on the effect of the oxide presence [135]. Using conductive sheets, common problems include the large crosstalk between adjacent cells and low accuracy [136]. Moreover, we chose to rely on pneumatic technology because it allows to create soft devices that can be used both as sensors and as actuators [137]. Relying on a pneumatic device, we can exploit the "actuation" capabilities of the soft modules to change their compliance. This can be done by suitably tuning the inflating pressure, as will be shown in Section 6.1.2 by the performed FEM simulations.

In our case, the possibility of inflating more or less the pneumatic chambers is fundamental, as it allows to adapt the stiffness of the modules to support and sense objects with different weights. A heavy object placed over an almost deflated module would squeeze it, generating a significant decrease of the height of the soft layer in correspondence to the object. This would imply that when the gripper touches the soft layer, there would be less space between the gripper tips and the rigid table, and thus the interaction might be less safe. A very heavy object would also generate a considerable increase of pressure in small volumes of air, reducing the capabilities of the contacted modules to detect the robot contact. For high inflating pressures, in fact, the modules are less sensitive to external deformations. For the same reason, light objects over stiff modules are hardly detected. Thus, adapting the compliance of the SoftPad to the object to grasp is beneficial from the sensing point of view because it allows to change the sensing parameters (e.g., measurement range, sensitivity, etc.), which can be adapted according to the mass of the object to maximize the sensing capabilities. Adapting the compliance to the objects would not be possible by simply placing a matrix of tactile sensors under a soft passive layer. In case of a passive soft layer, the only way to adapt the compliance would be to change the set-up, e.g., by changing the exploited material. In [138], soft actuation and soft sensing are combined for body pressure sensing and adjustment, but they are obtained with different technologies: while the actuation exploits two-balloon air cells, sensing is based on flexible capacitive pressure sensors.

Another advantage of using pneumatic systems is that the electronics can be delocalized, ensuring a high-temperature resistant and washable device in the work-space.

Previous works showed that pneumatic devices can effectively be used for force and pressure sensing. In addition to the works presented in the first part of this thesis, which are focused on surgery, in [139], for example, pneumatic chambers were used to detect obstacles with a robotic cleaner, whereas in [140] and [141] pneumatic cushions were used to measure forces exchanged between a human and a robotic system in two different scenarios. More recently, pneumatic sensors were developed for manipulation [142].

In this thesis, the previously presented works focus on adding softness and sensing capabilities to robotic tools themselves. Instead, in Chapter 6 we show that pneumatic sensing is a viable solution to create compliant and sensorized inclusions to instrument the environment for facilitating grasping tasks with rigid grippers. Besides presenting the design of a new soft sensorized device, this work introduces a scalable grasping strategy that exploits its features for grasping objects from the top.

While the aim of Chapter 6 was to describe the working principle of the Softpad, in Chapter 7 the behaviour of the device has been studied through Finite Element Analysis (FEA). Different models for non-linear materials have been compared in order to identify the most suitable to represent the relation between the deformation of one of its modules and the inflating pressure.

Chapter 6

A soft sensorized surface for exploiting environmental constraints with rigid grippers

As introduced in the previous chapter, a common trend in robotic manipulation is to build compliant hands that can exploit environmental constraints to perform robust grasps. However, in large-scale industrial applications, end-effectors are mostly rigid. Although soft robots have several advantages, rigid robots still present important features that are difficult to obtain with soft robots, such as the precision and repeatability of movements, as well as the possibility of having accurate measurements through sensors. How can we exploit environmental constraints using rigid industrial grippers?

In this context, the main contribution of this chapter consists in proposing, instead of sensorizing the individual fingers of a gripper, as for example in [143], to exploit soft inclusions in the environment to perform robust grasps with rigid grippers. In particular, making use of the SoftPad, a matrix of pneumatic modules connected to pressure sensors and placed beneath the object to grasp, it is possible to improve the chances of grasping objects despite the low compliance of the gripper. This is achieved through a grasping strategy that exploits such soft sensorized layer as a detection device. Thanks to this modular pneumatic surface, we propose to add compliance to the environment, and, in addition, pressure sensors connected to its silicone modules allow to estimate the object pose and center of mass and to detect the contact between the gripper and the object or the SoftPad itself during a grasping task. Thus, using the SoftPad implies two main aspects: *i)* adding softness to the environment to facilitate the grasp, *ii)* relying on pressure readings to locate the object and have information about its mass distribution.

In this chapter, a new grasp strategy that exploits such information for top-grasping objects, without using cameras or force sensors, is presented. This strategy has been tested with several objects having a wide range of sizes, shapes, and weights. Moreover, since one of the advantages of the SoftPad is that its design can easily be adapted to the set of objects that are used in a certain application, FEM models have been developed with the purpose of creating a simulation framework to find the most suitable modules properties and configuration.

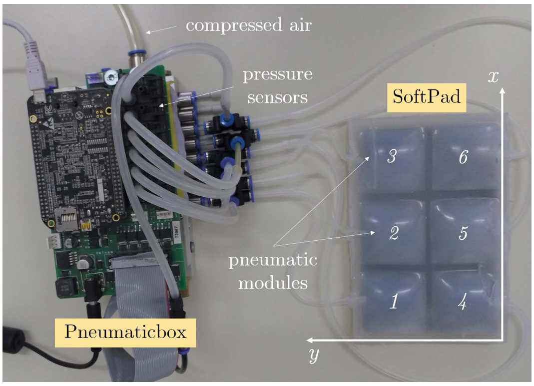


Figure 6.1: SoftPad and Pneumaticbox used in the experiments.

6.1 The SoftPad

In this section, the SoftPad structure and its manufacturing process are described. Then, a FEM simulation framework to study the device behavior is introduced. Here we will focus on the specific SoftPad that was built to test the grasping strategy described in Section 6.2 and that is shown in Fig. 6.1, but the device features (size, material, stiffness, etc.) can be customized depending on the specific application.

6.1.1 Device description

The proposed device consists of a 2×3 matrix of pneumatic modules. Each module is 45×45 mm, with a total height of 10 mm, of which 1.5 mm constitute the inflation layer. The overall size of the SoftPad is 165×115×10 mm. The size of the module can be chosen according to the required spatial resolution and to the size of the objects. Smaller objects, for instance, require smaller modules to properly detect their shape.

Regarding the spatial resolution, for such a pneumatic device it is related to the module inflatable area, but also to the minimum distance that can be obtained between two modules. In other words, two contact points are distinguishable only if they fall onto different modules; if they fall in the same one or in non sensitive parts (i.e., connections between modules), they cannot be distinguished. In our preliminary prototype the space between the inflatable areas of two modules is around 1 cm, and the inflatable area (45 mm×45 mm) has been chosen according to the set of objects we planned to use for the experiments. The spatial resolution can be increased by fabricating smaller modules