The DressGripper: A Collaborative Gripper With Electromagnetic Fingertips for Dressing Assistance

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***Abstract*—This letter introduces a collaborative gripper designed for safe interactions during wearing operations. In a robotic system helping people to get dressed, two main goals have to be achieved: *i)* the gripper that potentially comes in contact with the person has to be intrinsically safe and *ii)* the gripper should be able to keep the cloth during dressing, e.g. while passing the arm inside the sleeve of a jacket. This letter proposes the DressGripper, a gripper that addresses these issues by combining a compliant and safe structure with an additional magnetic actuation at the fingertips. This combination enables a soft interaction with the robot while guaranteeing the necessary grasping tightness. Experiments with the proposed prototype demonstrate its applicability in robotic dressing assistance scenarios.**

***Index Terms*—Grippers and other end-effectors, safety in HRI, soft robot applications.**

I. Introduction

ROBOT-ASSISTED dressing is a tight human-robot collaboration requiring the strict adoption of the principle "safety first". During dressing, the human and their robotic mate coexist in a very limited space, and can get in contact even unexpectedly. In collaborative tasks like this one, the robotic end-effector used to manipulate the clothes plays a key role, and soft robotic grippers should be employed [1]. Such end-effectors, indeed, are able to easily deform during interactions, being therefore able to absorb the energy of unexpected collisions, and allowing intrinsically safer interactions than those that can occur with rigid grippers. In this work, we present DressGripper, a soft-rigid gripper specifically designed for robot-assisted dressing, exploiting a novel synergistic interplay between tendon-driven and magnetic actuations (Fig. 1).

Fig. 1. The dressing setup, composed of a collaborative robot and the DressGripper, assisting a person in wearing a shirt.

Compliance in grippers can be attained in active or passive fashion. Active compliance is related to fully actuated (or hyper-actuated) rigid hands [2], [3], and can be obtained by controlling separately each joint. Despite the high accuracy achievable by these devices, mechanical and computational complexities are very high, affecting device reliability and usability. Higher robustness with lower mechanical complexity can be obtained by introducing passive compliance. In compliant hands, links and joints are at least partially made of elastomeric and flexible materials. Moreover, such devices are underactuated by design, meaning that they have less actuation sources (Degrees of Actuation, DoAs) than the Degrees of Freedom (DoFs).

Among compliant end-effectors, in soft-rigid devices ([4], [5]) passive elements are combined with a transmission system (composed of gears, pulleys and tendons) to distribute the actuation torque also to the underactuated joints [6], [7], making the latter be passively driven with kinematically constrained motion. This actuation strategy allows having grippers with links that, if accidentally hit, do not oppose strong resistance to the motion of the hitting part. Hence, the State of the Art for assistive grippers exploits the combination of hardware underactuation via mechanical coupling of joints, and deformable materials

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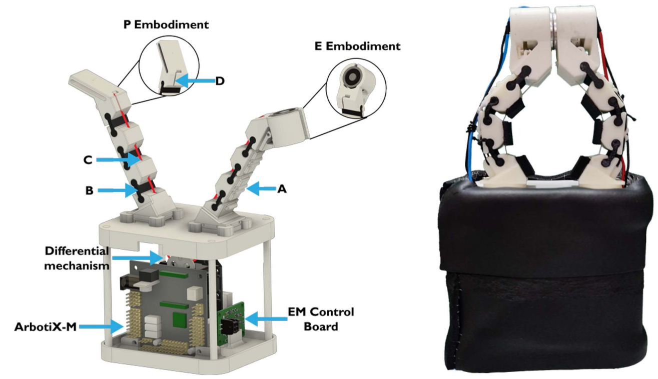
covering the device's rigid links, realizing a functional solution to the need of safe interactions. Moreover, in this way, part of the device "intelligence" can be *embodied* in the hardware design, instead of being exclusively allocated in the control algorithms [4], [8]. However, underactuated devices suffer from non-precise motion control and intrinsic incapability of strongly counteracting mechanical disturbances (e.g., undesired and unexpected forces possibly opening the jaws). Moreover, classic control strategies [9] can not be applied, due to the indeterminate kinematics of such devices and difficulties in modelling compliance and how the latter reflects on transmitted forces and torques in the device's components. To overcome such limitations, current research is steering again to complexity in design and control [10]: The basic idea is to provide the device with replicates of the actuation source (e.g., motors), with the drawback of increased encumbrance and the need of sophisticated control strategies.

In this work, instead, we propose a tendon-driven underactuated gripper with magnetic actuation, attained by embedding properly located magnetic elements, which can act as additional degrees of actuation (DoAs) operating in specific locations of the gripper. Hence, they can act synergistically with the more global effect provided by classic actuation and transmission components (like motors and tendons), arousing a complementarity enriching of the device's capabilities. The presented gripper is specifically designed for intrinsically safe human-robot cooperative dressing [11]. By "intrinsically" safe we mean that the gripper has to be capable of absorbing the impact of unexpected collisions with the human by deforming its structure, and then it has to restore its original configuration. Moreover, with "cooperation" we mean that the gripper has to enable the interaction between the robot and the human in order to achieve the common goal of dressing the human. Hence, the gripper has to ensure the grasp maintenance.

The letter is organised as follows: In Section I-A, state-of-the-art solutions for garment manipulation are outlined. In Section II, we present the DressGripper, its design and the FEM analysis carried out for characterization. In Section III, we discuss the experiments we performed to have insights on the actual DressGrippercapabilities while grasping different fabrics, and we also show a test conducted in a possible collaborative robotic dressing setup. Then, conclusions are drawn.

A. Related Works

Grasping and manipulating garments is a great challenge in robotics. Garments, indeed, are millimetric-thick objects with extremely high deformability. However, the vast majority of grippers used in garment manipulation are not specifically designed for interaction with fabrics [12]. In [13], a gripper for prehensile and non-prehensile grasping is proposed. In [14], needles are used to separate and grasp different layers of fabric. In [15], rolling fingertips are used to detect the corners of the fabric to facilitate the manipulative steps. In [16], suction cups are investigated. Multi-fingered-hands can allow more dexterous manipulation [17], [18], exploiting also device sensorization to perform material classification [19], or environment exploitation [20]. In [21], a jaw-gripper augmented with an electromagnet is used to perform repeatable autonomous manipulation of garments embedding ferromagnetic parts. However, none of these grippers are designed to allow safe human-robot interactions. Usually, garments are manipulated in industrial settings, where reliability, high-speed and accuracy are privileged.



(a) (b)

Fig. 2. The DressGripper: (a) CAD model, showing base, actuation mechanism, electronics, modular fingers, and fingertips embodiments ("A" rigid modules, "B" flexible joints, "C" tendon path, "E" electromagnet, "P" ferromagnetic plate). (b) EE embodiment of the DressGripperprototype, front view.

Cloth perception has been investigated in [22], [23]. Machine-Learning based techniques for autonomous manipulation of garments have been proposed for instance in [24]–[26]. However, these approaches are suitable only for manipulation without the presence of humans. In [27], [28] issues and standards for task-related physical human-robot interaction are discussed. In [11], guidelines for collaborative grippers are proposed. In this letter, we adopt such guidelines and present a gripper specifically designed for human-robot collaborative dressing.

II. The DressGripper

In this section, we provide details on the design of the DressGripper, whose CAD model is shown in Fig. 2. The DressGripperis an underactuated soft-rigid gripper composed of two modular fingers connected to a base, which contains all the electronic components. The DressGripperis specifically designed to exploit a synergy between tendon-driven and magnetic actuations. The fingers are tendon-actuated: the transmission system conveys the force from the motor to the fingers thanks to tendons connecting the motor to the fingers. The fingertips are equipped with magnetic elements that are the source of the magnetic actuation. Tendon-driven actuation allows the flexion/extension of the fingers, while magnetic actuation is in charge of empowering the contact permanence between the fingertips, reflecting on the tightness of the garment grasping.

Each finger of the DressGripperis a kinematic chain composed of two identical modules ending with a fingertip module. In one of the two fingers, such a fingertip module contains an electromagnet. On the other finger, the fingertip can contain two different elements: it can host another electromagnet, or it can house a small ferromagnetic plate (see Fig. 2(a)). The rationale is that the proper choice depends on the use-case. Electromagnets, indeed, are capable of exerting high grip (magnetic) forces but may have non-negligible power consumption, especially in prolonged use. Although higher forces allow manipulating heavy and thick clothes, high power consumption requires connecting the gripper to the power supply. The fingertip's embodiment exploiting only one electromagnet, instead, requires less power consumption, hence it is suitable for being used with a battery, and can be mounted also on a passive robotic arm. Grip forces will be usually lower than those generated by two electromagnets, hence this configuration is more suitable to thin and light garments. More details on the fingertip module will be provided in Subsection II-A.

Each module of the two fingers consists of a rigid part 3D-printed in Acrylonitrile Butadiene Styrene (ABS), indicated with "A" in Fig. 2(a), and a flexible part 3D-printed in thermoplastic polyurethane (TPU) (Lulzbot, USA) indicated with "B" in Fig. 2(a). Polyurethane was selected for its elongation and fatigue resistance properties, which allow repeated movements of the joints without remarkable wearing, and provides also a good damping ratio suitable for reducing undesired vibrations and absorbing shocks [29]. Part A and part B are connected one to each other by sliding part B inside part A, thanks to proper grooves located in part A. This modular approach allows quick and easy assembly process. Moreover, in each module we designed paths (denoted with "C" in Fig. 2(a)) to allow the insertion / extraction of the cable (polyethylene Dyneema fiber, Japan) exploited for the tendon-driven actuation.

Such a tendon-driven actuation is attained by using a motor and two tendons in parallel, marked in red in Fig. 2(a). In each tendon, one end is connected to the fingertip module (after having passed it through the intermediate modules of the fingers), while the other end is connected to a differential mechanism which, in turn, is connected to a pulley rigidly attached to a Dynamixel MX-28 T motor (Robotis, South Korea). The motor has a maximum torque of 3.1 Nm and a maximum angular speed of 11.9 rd/s. To control the DressGripper, an ArbotixM controller (Robotis, South Korea) is used, with the driver for the Dynamixel and the exploitation of an AVR microcontroller.

The rotational movement of the motor allows the cables to be wound around a pulley with a radius of 10.5 mm (see Fig. 2(a)), producing flexion of the fingers by reducing the length of the wires. Viceversa, the extension of the fingers occurs thanks to the elastic force stored in the flexible parts of the modules during the previous flexion. During this releasing step, the motor returns to its initial position.

Furthermore, each finger is connected to the base of the gripper through a dovetail joint which allows a complete rotation of the finger about its axis (perpendicular to the palm). Motor and electronic components, which represent critical elements from the robustness point of view, are positioned under the gripper base, in a safe position, well-protected from accidental shocks and contacts with the human.

The design of the two different embodiments of the fingertips is detailed in Section II-A; in Section II-B we describe the finger's trajectory design, and in Section II-C we report the results of the stationary structural analysis of DressGripperaccording to the Finite Element Method (FEM).

TABLE I
TECHNICAL FEATURES OF THE DRESSGRIPPER

Technical Features		
Weight (including motor)	488 g	
Actuator	Dynamixel MX-28T	
Max. actuator torque	3.1 Nm @ 12 V	
Max. current	1.4 A @ 12 V	
Continuous operating time	3.5 h @stall torque	
Max. operating angles	300 deg, endless turn	
Max. non-loaded velocity	11.9 rad/sec	
Electromagnet	ARD MAGNET-25N	
Electromagnet force	25 N @ 5 V	
Material properties	**Flexible joints**	**Rigid links**
Material type	TPU	ABS
Density	1200 kg/m^3	1070 kg/m^3
Modulus of elasticity (E)	15.2 MPa	40 MPa

A. Fingertips Design

Two versions of the DressGripperfingertips have been developed, and the relative CAD models are shown in Fig. 2(a). Both modules have the same lower part containing an internal path designed to route and fix the tendon for the actuation. The Electromagnet Embodiment (EE) is designed to host an electromagnet, whereas the Plate Embodiment (PE) houses a ferromagnetic plate. Both the fingertips are inclined 45 degrees with respect to the other intermediate modules of the fingers, with the aim of providing parallel surfaces after the flexion motion of the fingers, so to make the DressGrippersuitable for performing pinch grasps of garments, which are extremely thin objects. More details on the finger trajectory are reported in Section II-B.

The EE module (Fig. 2(a)) was designed to contain the electromagnet. An ARD MAGNET-25 N electromagnet with 25 N holding force at 5 V was selected to meet the requirements in terms of weight, strength, size and ease of control. In the PE (shown in Fig. 2(a)), the fingertip hosts a ferromagnetic plate. To avoid undesired interactions with ferromagnetic parts possibly embedded in the garment (like buttons, zip, studs, *etc.*) the material used is a soft ferromagnet, meaning that it does not have remarkable residual magnetization, but easily magnetizes when subjected to a magnetic field, and easily demagnetizes when the magnetic field is turned off. More specifically, we realized a plate of size 22 mm$\times$ 20 mm $\times$ 3 mm, composed of adjacent steel wires held together with a thin layer of glue gun, located at the bottom part of the plate and not covering its upper part (see Fig. 3(b)).

In addition, to compare the DressGripperwith a simple gripper without magnetic actuation, we considered also the NEP embodiment (No Electromagnet (nor) Plate), in which the gripper has only tendon-driven actuation, no magnetic elements are hosted in the fingertips, and the last module of the finger is similar to the intermediate ones (see Fig. 3(c)).

The main technical features of DressGripperare reported in Table I, while DressGripperprototype is shown in Fig. 2(b).

B. Finger Design Trajectory

The hardware design's key goal was to provide a solution allowing inherently safe interactions with humans. Hence, a

(a) (b) (c)

Fig. 3. The DressGripper with different fingertip embodiments: (a) EEE, two electromagnets are hosted in the fingertips, (b) EPE, an electromagnet is hosted in one tip, while the other houses a ferromagnetic plate, (c) NEPE, fingertips are simply covered with a rubber layer.

soft-rigid gripper with elastic joints has been realized. To print the prototype, we had to select the values of the joints' stiffness. Such values are strictly related to the specific gripper's topology, i.e. to the way in which the torque is transmitted from the motors to the entire fingers' structure. In this light, we constrained the problem as described in the following lines, keeping in mind that our goal was grasping garments. The two fingers of the DressGripperhave been designed to close by following a given flexion movement aimed at making the two fingertips be in parallel contact, allowing the DressGripperto perform the desired pinch grasp. Such a trajectory is tendon-driven actuated. Thanks to the flexible modular structure, it was possible to define the closing trajectory of the fingers by selecting the stiffness of the soft joints. In particular, this approach led to the identification of proper stiffness ratios between two consecutive joints, according to the procedure detailed in [30]. We exploited the tools provided by SynGrasp [31] to analyse the gripper kinematic properties, and in the following we discuss the main equations adopted for the analysis.

Let us consider the two fingers of the DressGripperactuated by n_t tendons, where each tendon connects n_q joints. In [32], a three-dimensional analysis of the deformation of the flexible joint is reported, however, in this work for the sake of simplicity we assume that the soft joint is a revolute joint, neglecting other possible deformations. Hence, the variable q_i, which describes the displacement of the $i-th$ joints, is a pure rotation angle. Let us define the vector that contains the rotations of the gripper joints $\mathbf{q} = [q_1, \ldots, q_{n_q}]^T \in \mathbb{R}^{\mathrm{n_q}}$, and the vector related to the displacement of the tendons, that is denoted with $\boldsymbol{\delta} \in \mathbb{R}^{\mathrm{n_t}}$. Through $\boldsymbol{\delta} = \mathbf{A}\mathbf{q}$ we indicate the relation between the displacement $\boldsymbol{\delta}$ of the tendon and the configuration of the gripper joints q, with $\mathbf{A}$ being a transformation matrix defined by the size of the finger's pulley and by the topology of the tendon routing [6]. Using the Principle of Virtual Work, it turns out

$$\boldsymbol{\tau} = \mathbf{A}^T\mathbf{f}, \tag{1}$$

where $\boldsymbol{\tau}$ is the vector containing the joint torques, while $\mathbf{f}$ is the vector of the tendons' pulling forces. Assuming that the gripper moves the fingers without interacting with any object or external surfaces, and that no external forces are present, the relation between the gripper configuration and the torque at the joints is described by

$$\boldsymbol{\tau} + \mathbf{K}_q\Delta\mathbf{q} = 0. \tag{2}$$

$\mathbf{K_q} \in \mathbb{R}^{\mathrm{n_q}\times\mathrm{n_q}}$ is the joint stiffness matrix (symmetric and positive definite), while $\Delta\mathbf{q}$ denotes a variation of the joints configuration with respect to a reference rest position $\mathbf{q_0}$ of the gripper, i.e., $\Delta\mathbf{q} = \mathbf{q} - \mathbf{q_0}$. If the joints are independent, $\mathbf{K_q}$ is diagonal and by assuming $\mathbf{q_0} = 0$ the Eq. (2) can be rewritten as

$$\boldsymbol{\tau} + \mathbf{Q}\mathbf{k_q} = 0, \tag{3}$$

where $\mathbf{Q} = diag(\mathbf{q})$ with $\mathbf{Q} \in \mathbb{R}^{\mathrm{n_q}\times\mathrm{n_q}}$, while $\mathbf{k_q} \in \mathbb{R}^{\mathrm{n_q}}$ is the vector of the joint stiffness. Taking into account eq. (1), the the joints stiffness can be retrieved as

$$\mathbf{k_q} = \mathbf{Q^{-1}A^Tf_r}. \tag{4}$$

Such a solution contains the stiffness values for the flexible joints of the gripper, allowing to obtain the configuration $\mathbf{q_r}$ of the joints given the force $\mathbf{f_r}$ applied by the tendons. Moreover, to obtain a base for the subspace of possible stiffness combinations that can be used to perform a desired trajectory, the vector $\mathbf{k_q}$ has to be normalized. As previously mentioned, the shape of the finger trajectory depends on the stiffness ratio between two consecutive joints where, in order to obtain a complete trajectory, a sequence of configurations must be evaluated, leading to a sequence of $\mathbf{k_q}$ values. However, in [30], it is shown that for several closing trajectories, similar to the ones that have to be realised with DressGripper, the values in $\mathbf{k_q}$ have a slight fluctuation during the completion of the finger flexion. Hence, to make the flexible joints, we considered the average over all the retrieved $\mathbf{k_q}$ values, which results in an acceptable error on the tracking trajectory [30]. Then, we exploited the potentialities of 3D printing to create flexible joints for the DressGripperby suitably varying the infill density percentage parameter, which modifies not only the density of the material but also its mechanical properties (e.g. the Young's modulus). Fig. 4 shows the result of the simulation made with SynGrasp to create the desired trajectory.

C. Finite Element Analysis

Here we report the results of the structural analysis conducted in terms of stress and displacement for providing a characterization of DressGripperin conditions of interest. The analysis focuses on the entire structure composed by the two fingers as well as on a single finger. Both EE and EP embodiments have been considered, and the resultant grippers will be denoted with "EEE" when two EE are considered and with "EPE" when an EE and an EP are assembled (Electromagnet and Plate Embodiment), see Fig. 3. The Finite Element Analysis was conducted in the D-CAD/CAE Autodesk Fusion 360 software, and materials used were the same of Section II-A. Since the DressGripper's base is not actuated, in the following we neglected its dynamics.

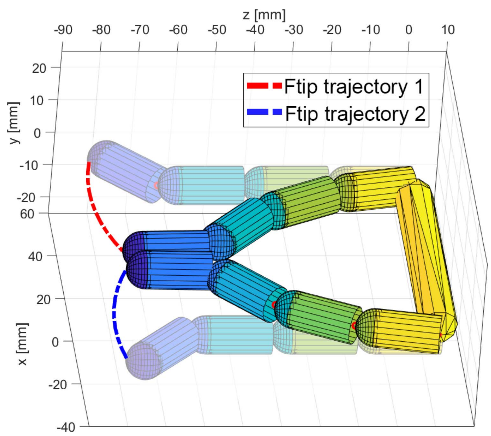


Fig. 4. Fingers' trajectory: initial and final configurations, simulated in SynGrasp.

Focus on Magnetic Attraction. To simulate the synergistic interplay between tendon-driven and magnetic actuations, we assumed to have activated the motor for closing the fingers until the tips almost touched each other. Then, we estimated the force required to make the fingers be in contact. FEM simulations were carried out applying forces at the fingertips in the range [0.5, 1.5] N.

First, we consider the EPE in the case in which the ferromagnetic plate and the electromagnet are distant 3 mm. Since the plate is made of a soft ferromagnetic material, the magnetic field generated by the electromagnet is channelled orthogonally to the plate. Hence, a force perpendicular to its surface was simulated. FEM analysis revealed that 1 N is sufficient to make the fingers be in contact, as shown in Fig. 5(e). Then, we considered the EEE. Since the magnetic attraction between two electromagnets is stronger than the attraction between an electromagnet and a soft ferromagnetic material, we allowed a greater distance between the two magnetic elements, i.e. we selected 6 mm. Fig. 5(d) shows that also in this case a force of 1 N is sufficient to make the fingers contact each other. These results provide the requirement in terms of force that the electromagnet has to satisfy. More details on the validation of the electromagnet are in Section III.

Focus on Robustness to Perturbations. To investigate the robustness of the fingertip structure, we applied forces at its tip, since this is the part of the finger stressed the most during the use of DressGripper. A force of 10 N [33] was applied in a direction perpendicular to the surface devoted to the contact. Such a force is meant to be a conservative estimate of the force resulting from a possible (undesired) force applied by the human during the wearing, and the force of attraction between the magnetic elements. The first force just mentioned acts as grasp-breaking force, while the second corresponds to an attraction. EE and EP embodiments were investigated, and results are shown in Fig. 5(f) and Fig. 5(g). It is worth to notice that the maximum equivalent stress that can be sustained by standard ABS and TPU is 60 MPa and 50 MPa, respectively. Results show that both the finger embodiments are strong enough to resist to the simulated forces.

Moreover, we carried out an investigation aimed at evaluating the robustness of the gripper when subjected to the weight force of the garments and to possible tangential disturbances generated by undesired collisions between the garment and the human that is wearing the garment with the aid of the robot. Such forces, indeed, can lead to a grasp break due to sliding. To have insights on these aspects, we selected four fabrics used in Section III, i.e. "Undershirt1", "Shirt1", "Fleece" and "Jeans", that were considered to be representative fabrics. By following the procedure detailed in Section III, we estimated conservatively the average sliding force, i.e. the average force that is required to break the grasp by stretching the fabric until it slides (see Fig. 6). EEE, EPE and NEPE were investigated, and we found average forces of about 5 N, 2 N and 1 N, respectively. Such values have been used as estimates of the above mentioned tangential disturbances. Concerning the weight force of the garment, we conservatively simulated a magnitude of 5 N (corresponding to a garment with a mass of 500 g).

The Fig. 5(a), Fig. 5(b) and Fig. 5(c) show how the fingertip embodiment affects the stress the gripper is subjected to. In particular, in Fig. 5(b) there is a maximum Von Mises of 18.9 MPa, while in Fig. 5(c) there is a maximum Von Mises of 13.6 MPa, which is the minimum stress among all of three results. However, in all the fingertip embodiments, the structure resists and has a Von Mises value lower than the maximum allowable value for the considered materials.

III. Experiments

In this section, we report the experiments carried out to investigate the DressGrippergrasping capabilities.

To compute analytically the force of attraction between the electromagnets or between electromagnet and ferromagnetic plate, all the specifications of the electromagnets have to be known, as well as the magnetic permeability of the ferromagnetic materials. However, informations on the internal structure of the electromagnet are not disclosed by producers, due to property protection policies. Hence, we experimentally characterized our setup.

Estimate of Magnetic Attraction. The DressGripperwas actuated so to have a distance between the fingertips of 6 mm and 3 mm while exploiting EEE and EEP configurations, respectively (see Section II-C). Such a distance was measured by means of a calliper with a resolution 0.1 mm. One electromagnet was constrained by using a g-clamp, whereas the second magnetic element (the other electromagnet or the ferromagnetic plate) was left free of moving. The non-constrained element was attached to a strain-gauge based dynamometer (dual-range Vernier dynamometer - Vernier Software & Technology, US) with an accuracy ± 0.05 N, through a non-extensible wire (Fig. 8(a)). The distance between the fingertips was checked again, and then the electromagnet(s) was (were) activated. Due to magnetic attraction, the non-constrained finger feels an attractive force, measured by the dynamometer. Data were acquired at 200 Hz, and the experiment was repeated 5 times for each configuration. Fig. 8(b) shows the force read by the dynamometer. Average values are (0.92 ± 0.06) N and (0.75 ± 0.08) N for the EEE

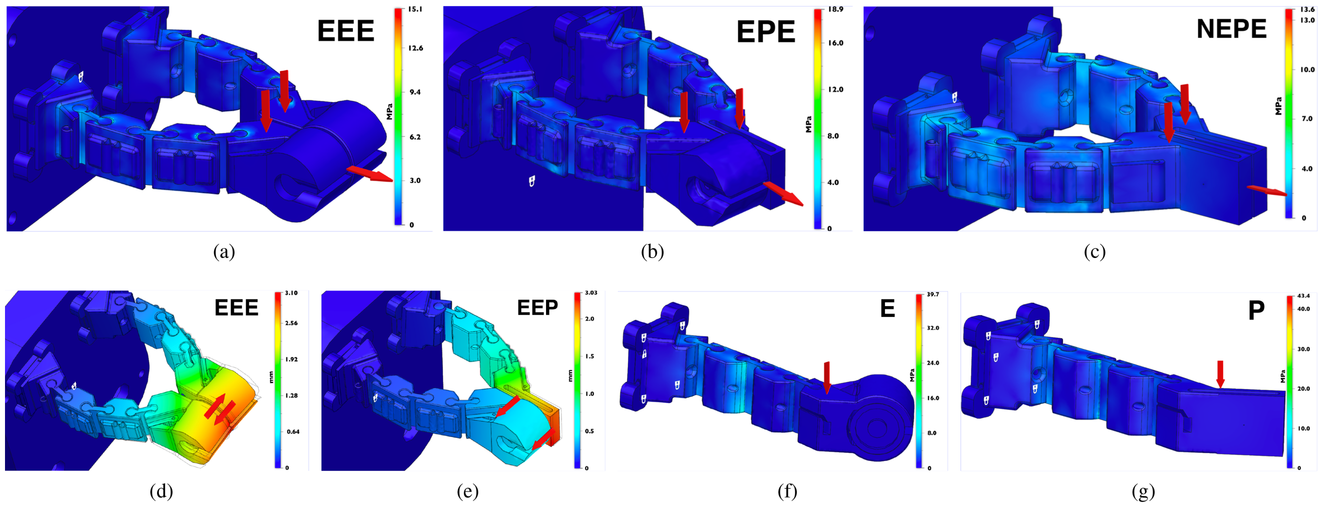


Fig. 5. Results of the FEM structural analysis. In (a)–(c) Equivalent Von Mises stress distributions when 5 N of garment weight force is applied in addition to 5 N (a), 2 N (b) and 1 N (c) of tangential disturbances forces, respectively. (d) and (e) report the FEM structural analyses when 1 N force at the fingertips surfaces are applied, while (f) and (g) show the Equivalent Von Mises stress distribution when 10 N force is applied. Red arrows indicate the forces applied, while the transparent wireframe CAD model shown in (d) and (e) is the reference undeformed model. The colored surface corresponds to an "actual" deformation of the DressGripper's fingers.

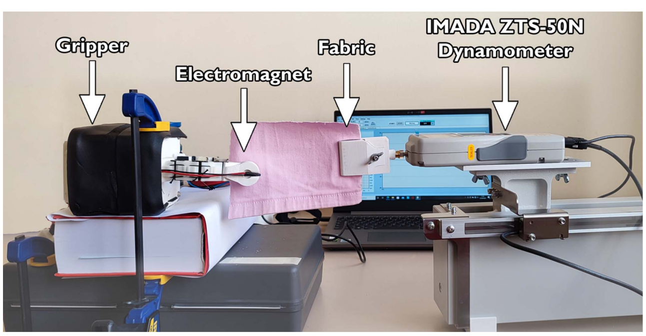


Fig. 6. Experimental setup for testing the DressGripper capabilities when grasping different types of fabrics. Forces needed to break the grasp have been estimated. Here we report the specific case where the EEE type DressGripper is tested.

TABLE II
FABRICS USED FOR CHARACTERIZING THE DRESSGRIPPERCAPABILITIES. IN THE LAST THREE COLUMNS, WE REPORT THE AVERAGE FORCE REQUIRED TO BREAK THE GRASP IN THE NEP, EP AND EE EMBODIMENTS. "W" AND "T" STAND FOR "WEIGHT" AND "THICKNESS" OF THE GARMENT, RESPECTIVELY

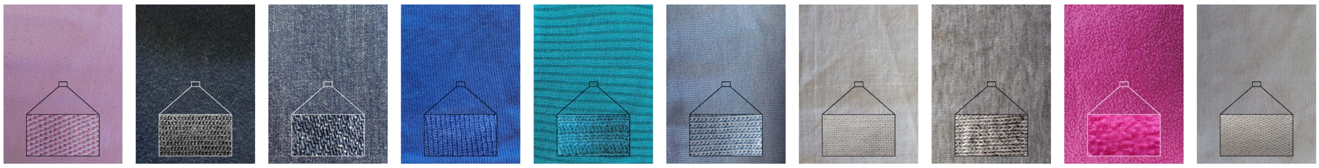
Sample	W [g]	T [mm]	F_{NEPE} [N]	F_{EPE} [N]	F_{EEE} [N]
Trousers 1	6.23	0.62	0.83±0.23	1.41±0.16	2.19±0.38
Trousers 2	7,80	0.94	0.93±0.29	1.17±0.13	1.74±0.10
Jeans	7.07	0.72	0.97±0.26	1.33±0.25	3.12±0.34
Undersh1	5.77	0.70	1.08±0.13	1.66±0.17	4.60±0.57
Undersh 2	2.81	0.70	1.32±0.18	2.86±0.16	9.85±0.48
T-Shirt	2.46	0.52	1.25±0.10	2.66±0.03	7.52±0.68
Shirt 1	2.27	0.26	1.04±0.26	1.77±0.14	9.21±0.25
Shirt 2	4.50	0.66	1.01±0.03	1.59±0.17	5.18±0.41
Fleece	3.85	1.10	1.53±0.13	1.61±0.06	5.69±0.46
Sweater	3.92	1.06	1.18±0.25	1.48±0.14	4.34±0.13

and EPE configurations, respectively. Such results are consistent with what was retrieved in the FEM analysis reported in Section II.

Focus on Tangential Forces breaking the grasp. To have insights on the actual performance of the DressGripperwhen manipulating fabrics, we selected 10 samples of fabric commonly used for clothes (Fig. 7), whose weight and thickness are reported in Table II (average size of fabric sample (80 mm±7) mm × (240±5) mm. Trousers are made of stretch cotton, with "Trouser1" more elastic than "Trouser2". "Jeans" are the less stretchy trousers. "Shirt1" is made of pure cotton, while "Shirt2" is a stretchy material containing elastane, cotton and polyester. "Fleece" is 100% polyester. "Undershirt1" is made of cotton 98%, elastane 2%, with very narrow ribs, while "Undershirt2" is made of cotton 95% and 5% elastane, and has ribs large 2 mm. "T-shirt" is made of cotton 98% and 2% elastane.

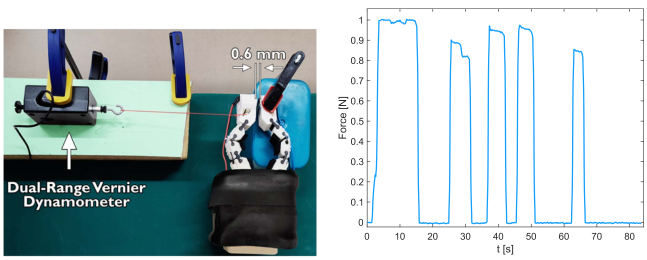
Concerning the experimental procedure, experiments were aimed at testing the DressGripper's ability to resist perturbations while pinch grasping different fabrics. A clip was attached to the fabric, and a dynamometer was attached to that clip. Forces were applied to the fabrics, using an IMADA ZTS-50 N dynamometer with accuracy ±0.01 N, fixed to a manual test stand HV-500 N II. The test stand was equipped with a linear encoder DMK for displacement measurement (accuracy ±0.03 mm). Once the fingers were closed, the fabrics between the fingertips were trapped. Tractions were exerted on the fabric until the sample began to slide. The procedure was repeated 10 times, and then forces were averaged. Results for the EEE, EPE and NEPE configurations are reported in Table II, where it can be noticed that the force needed to break the grasp in the NEPE configuration is the lowest among the finger fingertips' embodiments, and is rather independent on the type of fabric. This suggest that it is related to the underactuated structure of the gripper. Among the embodiments, EE provides the strongest forces, whereas the EP approach provides intermediate results, highlighting the dependency on the magnetic permeability of the selected plate.

Concerning garment types, trousers (Fig. 7(a), (b), (c)) are the clothes that slide the most. This can be due to the fact that the fabric weave is dense and combed. The sweater (Fig. 7(j))



(a) Trousers 1 (b) Trousers 2 (c) Jeans (d) Undersh 1 (e) Undersh 2 (f) T-Shirt (g) Shirt 1 (h) Shirt 2 (i) Fleece (j) Sweater

Fig. 7. Samples of fabrics used in the experiments on the actual capabilities of DressGripper.



(a) (b)

Fig. 8. (a) Setup for the estimate of the attractive force acting on the magnetic elements. (b) Attractive force on EE embodiment when the tips are distant 6 mm.

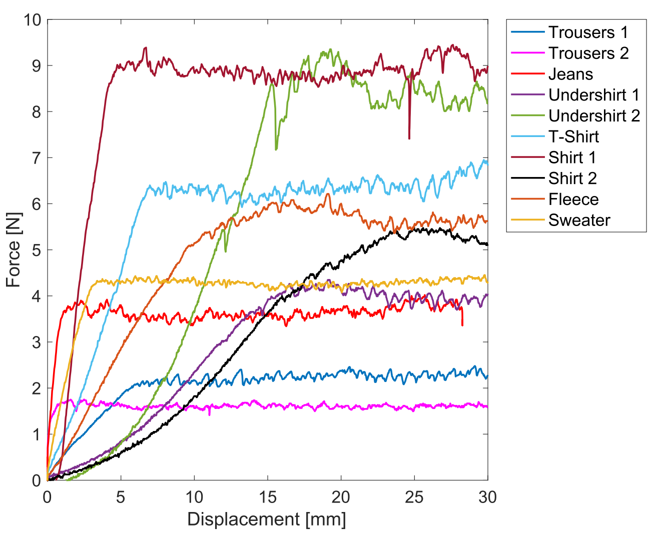


Fig. 9. Forces exterted on different fabrics while performing tractions aimed at retrieving insights on the DressGripper capabilities.

is made of microfiber with some friction, however, its weave is dense, hence, it produces intermediate results in terms of F_{EEE} and F_{EPE}. The fleece (Fig. 7(i)) is made of light fabric, however, also its weft is dense but sparser than the above mentioned materials. Little protrusions and the slippery behaviour of polyester reduce the adherence of the fabric to the fingertips. Hence, intermediate performance are obtained. The other garments, that perform better, are mainly made of cotton, have a sparser weft and are thinner (Fig. 7(d), (f), (g)).

Additional considerations regard the EE embodiment. Fig. 9 shows how the fabric material reflects on the traction applied by the HV-500 N: When the HV-500 N wheel rotates, an increasing force is applied to the fabric, until the fabric starts sliding and a plateau related to dynamic friction is reached. As it can be seen in Fig. 9, non-stretchy samples slide early. This trend applies to Jeans, Trousers2, Shirt1 and Sweater. The more evident (Undershirt2, see Fig. 7(e)) and sharp (Undershirt1, Undershirt2) is the ribbed pattern, the earlier the grasp breaks. The flatter and homogeneous the pattern is (T-Shirt and Shirt1), the higher the breaking force. Under similar pattern, the stretcher the fabric, the lower the breaking force (T-Shirt vs Shirt1).

Fleece, Undershirt1 e Shirt2 (Fig. 7(h)) show a similar behaviour, although the former starts sliding earlier. All of them are somehow stretchy, however, the fleece has a highly inhomogeneous pattern. Among these three fabrics, the fleence has the highest breaking forces, due to the low thickness of the fabric which allows stronger attraction between the electromagnets. However, it breaks earlier due to the relatively low stretch of the material.

Experiments reveal that thickness is not the only parameter that has to be considered to gain insights on the force required to break the grasp. Relevant characteristics are *i)* the fabric slip, *ii)* the pattern of the garment in the vertical direction, *iii)* the fibers' density. Concerning *i)*, the more man-made fibers are present, the more the fabric is slippery (as it can be noticed also by touching the fabric with hands). Regarding *ii)*, the more irregular the arrangement of full and empty spaces is along the vertical direction (e.g., in the fleece), the more easily the grasp breaks. Concerning *iii)*, the denser the fabric in both the horizontal plane and the vertical direction, the stronger should be the magnetic force to ensure the grasp maintenance.

To have insights on the DressGrippercapabilities during robot-assisted dressing, we implemented a human-robot cooperative scenario, exploiting the collaborative 7-DoF Sawyer robotic arm (Rethink Robotics). Since we were using a non-passive robot, we exploited the EEE DressGripperconfiguration, which proved to resist more than the EPE. Through kinesthetic teaching, we recorded a trajectory of the robotic arm aimed at helping a human to wear the sleeve of a shirt. For this test, we used a shirt different from the ones used in the previous subsections. The human is supposed to have one of his/her arm almost straight in front of him/her, while the robot grasps the shirt near the neck and gently moves towards the human, successfully fitting the sleeve on the human arm.

IV. Conclusion

Robotic dressing assistance is a particular type of collaborative robotic task where the robot end-effector is likely to become in contact with the user body. For this reason, the gripper cannot be rigid and solutions exploiting an intrinsic safety, e.g.

soft grippers, must be used. On the other side, during dressing operations, the grasp of the garment has to resist disturbance forces that may reach high values and that could be hardly resisted by soft structures.

In this work, we presented the DressGripper, a collaborative gripper specifically designed to provide robotic dressing assistance. The gripper is underactuated and exploits a synergy between tendon-driven and magnetic actuation. Magnetic actuation is achieved by using magnetic elements hosted in the fingertips. Two different embodiments have been proposed: EE, with two electromagnets, and EP, which exploits the presence of one electromagnet and a soft ferromagnetic plate. The former solution has lower power consumption, hence can be used with a battery in use-cases involving passive supports. FEM analysis has been conducted to characterize the gripper, and experiments have been carried out to have insights on the DressGripper-capabilities when grasping different types of fabric. The EE embodiment allows exerting stronger gripping forces for grasp maintenance, although with the drawback of higher power consumption with respect to the EP embodiment. A comparison with a state-of-the-art approach [11] shows that the synergy of magnetic and tendon-driven actuations outperforms the classic tendon-driven approach.

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