Differentiated layer design to modify the compliance of soft pads for robotic limbs

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Abstract—Most of robotic soft pads studied so far were made with a thick layer of homogeneous material shaped around a rigid core; their behavior has been widely investigated in the literature, mainly under compressive contact load, showing typical non-linear relationship between contact deformation and applied load (the so called power law). This paper proposes differentiated layer design, that is the adoption of a single elastic material, dividing the overall thickness of the pad into layers with different structural design (e.g. a continuous skin layer coupled with an internal layer with voids). The purpose is to modify the actual pad compliance and the resulting power law; in particular, given the material and the allowable pad thickness, to increase the compliance with respect to a non-structured pad. Some possible internal layer structures are described, compatible with rapid prototyping manufacturing. Their compressive behaviors are tested and comparatively evaluated showing that the concept can work and be exploited for useful application.

Index Terms—Robotic hands, soft fingers, fingertip design, experimental analysis

I. INTRODUCTION

Soft covers for robotic limbs are attracting growing interest of designers for several reasons. First of all, functional interaction between the robot and the external world during task accomplishment. A properly compliant surface is very useful and sometimes necessary when a robotic limb contacts an object for manipulation purpose. Local compliance determines contact extension and stiffness, therefore contact robustness and it allows local shape adaptation, thus overcoming very critical situations of contact stability, e.g. in the case of contact on edges or morphological object irregularities. Furthermore, a large pad deformation in the contact region can reduce contact pressure and material stress and better contribute to energy dissipation in case of vibration. In the literature the many benefits of local compliance have been widely commented (see e.g. [1], [2], [3]). A second important reason is related to intrinsic safety in the interaction of robot with living beings or with other robots, a theme of growing interest, in particular for humanoid robots called to daily interaction with humans. A non negligible contribution to the reduction of damage in case of accidental interference can be provided by soft pads, capable to distribute impact effects over a large deformed area, lowering local pressure peaks. Differently from active safety devices, like joints with controllable impedance, passive systems like soft pads can act in case of failure or functional emergency. A third important reason concerns the robot aesthetics and its perception by humans. Soft covers, warm to touch, can attenuate the impression of the humanoid robot as a machine, probably helping acceptance of robots by humans in everyday life. After early work on hemispherical coreless pads, recent work [4] [5] reported the behavior of pads composed by a layer of visco-elastic or simply elastic material shaped over an internal rigid core; this situation is more realistic with respect to application, as in most practical cases, like finger pads, palms or arm pads, an internal rigid structure is present, similarly to biological models. As demonstrated in Fig. 1 (from [6]) given the external geometry, the parameters that mainly contribute to the determination of the power law are the elastic material hardness and the layer thickness.

A reduction of material hardness, given the layer thickness, acts in favor of a compliance increase, but can generate problems in terms of surface tribology and reliability. On the other side, given the material, thickness reduction causes a reduction of the pad compliance, which means reduction of contact area under a given load, with downgraded contact robustness. As a matter of fact, thickness reduction is a significant goal for the robotic limb designer, that cannot easily reduce the overall size of the internal rigid core (hosting actuators, transmissions, sensors, etc.) but wants to obtain
slender bio-mimetic limbs at the same time. A good example of such problems can be found in the design of fingers for humanoid robot hands. The search of an acceptable trade-off between material properties and layer thickness is a commonly adopted solution. Another promising way may be to design pads with differentiated structure, that are composed by coupled layers of different materials or, adopting a single material, with different structural design of each layer. Of course, both these possibilities can be joined (different materials and different layer structures). The authors have been attracted by the design of differentiated layers made with a single material: this interest has been stimulated by the recent availability of elastic materials compatible with stereo-lithographic processes (rapid prototyping), so that the implementation of items with very complex shape can result relatively easy, fast and cheap. The target is to increase the pad compliance, and therefore contact areas for a given load, while maintaining the same dimensions for the inner rigid core and for the outer pad surface (i.e. pad overall thickness). A larger contact area is in fact proven to be beneficiary in term of grasp capability [7]. Nothing similar was found in previous literature, therefore an experimental investigation programme had to be defined and implemented.

II. DESIGN OF DIFFERENTIATED STRUCTURE PADS

The authors are involved in research projects (Dexmart European project and PRIN Sicura project) aiming, in the frame of more general goals as manipulation dexterity and safe human robot interaction, to the development of new generations of dexterous robotic hands. Consequently, the work reported in this paper is focused on design of pads having shape and size compatible with application on the fingers of a robotic hand similar in size to a human hand. In order to make the results directly comparable with previous investigations, the items to be tested were designed with the same dimensions adopted by [5] and the same testing procedures were employed. The basic concept of a differentiated structure pad is sketched in Fig. 2.

![Fig. 2. Concept behind the proposed solution. 3D model (a), longitudinal cross section (b).](image)

Given the geometry of the soft pad and its internal core, an external continuous layer covers an intermediate layer that presents voids, so that its apparent stiffness can be modified according to the design and distribution of such voids. They may simply contain air or can be filled with incompressible viscous liquids, with additional effects of very high potential interest. Four basic design patterns were developed and tested, as described in Fig. 3, a, b, c, d:

- Pattern with equally spaced hemispherical protrusions (Pad I).
- Pattern with equally spaced hemispherical voids (Pad II).
- Pattern with circumferential ribs connecting the core to the external layer (Pad III). Each rib is inclined of 45° with respect to the normal to the external surface, thus transforming normal loads acting on the contact into bending actions applied on each rib.
- Pattern with a series of inclined micro-beams, fundamentally subjected to bending (Pad IV).

![Fig. 3. Differentiated pad design (a,b,c,d).](image)

These four designs were developed so far as a proof of concept and on the base of intuition. These geometric configurations can be improved by FEM analysis, currently in progress. In the following Pad V will indicate a specimen with uniform layer (i.e. without any void).

Two types of elastic materials were available and tested:

- **Tango Gray**™ with tensile strength of 4.36 MPa, elongation at break of 47%, hardness 75 Shore A.
- **Tango Plus**™ with tensile strength of 1.50 MPa, elongation at break of 218%, hardness 27 Shore A.

Note that hyper-elastic constitutive laws (e.g. Ogden models [8]) for incompressible media should be used to describe the mechanical behavior of both materials. Therefore the Young modulus cannot be defined whereas the Poisson’s coefficient is \( \nu = 0.5 \). A pad made with Tango Gray™ will be referred to using the suffix \( a \) (e.g. Pad I\( _a \)) whereas a pad made with Tango Plus™ will be referred to using the suffix \( b \).

Both materials are photosensitive polymers that can pass from liquid to solid state under exposure to UV rays during the stereo deposition process. Deposition is made on layers of 0.030 mm thickness, which can provide acceptable dimensional tolerance and surface roughness of the generated item. Because in case of negative slope of lateral surfaces a sustaining additional material (a removable wax) must be deposited, the voids cannot be closed, therefore closed-cell structures, like foams, cannot be obtained with this technology.
As widely commented in a previous paper [9] a complete characterization of a robotic pad must include investigation on many properties and behavioral aspects. However a primary role is played by the behavior of the pad under normal contact load, in interaction with a rigid object, determining the relationship between the load and contact penetration. This early stage of investigation has been limited to preliminary analysis of static behavior. For each material, tests have been performed both analyzing contact on the hemispherical end of the pad and contact on the cylindrical part of it. To this purpose a cylindrical pad has been pressed against a rigid surface. Two types of rigid surfaces have been used: rigid spherical surface and rigid flat surface. In total four test procedures have been carried out:

1) Hemispherical pad against rigid flat surface.
2) Hemispherical pad against rigid hemispherical surface.
3) Cylindrical pad against rigid flat surface.
4) Cylindrical pad against rigid hemispherical surface.

The operating modes related to test procedures 2) and 3) are sketched in Fig. 4.

Examples of the achievable results are illustrated in the following figures. Figure 7 shows the experimental relationship between the normal load (N) and the resulting flattening (mm) of the specimens for the four different designs shown in Fig. 3 and for both the employed materials. It can be observed that all the pads present a self-hardening behavior which is enhanced by the presence of the rigid core. Moreover, as expected, the specimen stiffness heavily depends both on the material properties (especially hardness) and on the intermediate layer design. For a given pad thickness, a proper choice of such design can enhance the self-hardening behavior of the pads.

Control strategies suitable to exploit the self-hardening behavior of compliant pulps according to the different phases of manipulation have been discussed in [6].

The Pad V presents the highest apparent stiffness, followed subsequently by Pad II, Pad I, Pad III and Pad IV.

Figure 8 shows the experimental relationship between the normal load (N) and the resulting flattening (mm) of the same specimen (Pad I') for the different contact situations described in Section III. It can be seen that the curves significantly change quantitatively but maintain the same qualitative shape suggesting the possibility to derive a common model.
model the elastic response of the human fingertip. By assuming the power law model, the relationship between the normal load, \( N \) and the flattening, \( \delta \) is modeled through the function

\[
N = \alpha \cdot \delta^\beta
\]

where \( \alpha \) and \( \beta \) are constants, depending on the material and the design of the pad, that are determined from the experimental measurements. In this case the normal stiffness \( K_n \) follows the relation:

\[
K_n = \frac{dN}{d\delta} = \alpha \cdot \beta \cdot \delta^{\beta-1} = \gamma \cdot N^{\beta-1}
\]

where \( \gamma = \beta \cdot \alpha^{\frac{1}{\beta}} \). For the second model, by assuming the exponential law, the relationship between the normal load and the flattening is modeled through the function

\[
N = \frac{\eta}{\nu} \cdot \left(e^{\nu \delta} - 1\right)
\]

where \( \eta \) and \( \nu \) are constants that are determined from the experimental measurements. Consequently, the normal stiffness follows the relations

\[
K_n = \frac{dN}{d\delta} = \eta \cdot e^{\nu \delta} = \nu \cdot N + \eta
\]

Figures 9a and 10a show the relationship between the applied normal force \( N \) and the consequent flattening for Pads I_a, Pads II_a, and Pads III_a when the hemispherical specimen is pressed against a flat rigid surface. The continuous lines represent the fitting of the experimental data using the power-law (eq. 2) and the exponential model (eq. 4) respectively. Figures 9b and 10b show how the contact apparent stiffness \( K_n = \frac{dN}{d\delta} \) varies depending on the value of \( N \) for the same specimens.

The identification of the parameters of the two models is performed by means the least square method as described in [4]. The parameters \( \alpha \) and \( \beta \) in (1) and (2) are determined by directly fitting the experimental measurements reported in logarithmic scale. The obtained values for Pads I_a, Pads II_a, and Pads III_a (test type 1) are shown in Table I as an example. The parameters \( \eta \) and \( \nu \) in eq. (3) and eq. (4) are obtained with a different procedure. First, the experimental values of flattening vs. normal force are interpolated by a polynomial function of fourth order; then the force is numerically differentiated with respect to flattening and, by adopting equation (4), the parameters \( \eta \) and \( \nu \) are obtained by means of the least square method; their values for Pads I_a, Pads II_a, and Pads III_a (test type 1) are reported in Table I as an example. By comparing the experimental results and the theoretical models, it is found that the exponential equation (3) fits better the behavior of Pad I, II and III.

The behavior of Pad IV, on the other hand can be reduced neither to the power law model nor to the exponential model. In the case of Pad IV, a closer look to experimental results suggest the use of a piecewise function of the kind

\[
N = \begin{cases} 
\alpha \cdot \delta + b, & \delta < \delta_1 \\
\frac{\beta_1}{\beta_2} \cdot (e^{\nu_1 (\delta_1 - \delta)} - 1) + \alpha \cdot \delta_1 + b, & \delta \geq \delta_1 
\end{cases}
\]

for their behavior.

To model the behavior of the specimens under compression along the direction of the load, two well known models have been used and compared in order to evaluate their applicability in case of differentiated layer design. The first model is the power law equation proposed by Li and Kao [10] and adopted to model the normal stiffness of homogeneous hemispherical robotic fingertip; the second is the exponential law proposed by Pawluk and Howe [11] and adopted to...
where \( a, b, \eta_1, \gamma_1, \) and \( \delta_1 \) are constants to be determined experimentally. Figure 11 show the relationship between the applied normal force \( N \) and the consequent flattening for Pads IV (test type 1). The continuous line represent the fitting of the experimental data using eq. 5. The values of the constants are reported in Table II as an example.

V. COMMENTS

Design of different structures for the pad layers resulted an efficient way to modify its behavior, as demonstrated by the above described experimental curves. As expected, increasing the percentage of voids with respect to the overall layer volume causes a reduction of the resultant compressive stiffness; this effect is more evident in the cases where the walls that separate internal voids are working under bend-}

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**Table I**

VALUES OF THE CONSTANTS FOR EQUATIONS (1), (2) AND (3), (4), TEST TYPE 1, MATERIAL Tango Gray

<table>
<thead>
<tr>
<th>Specimen</th>
<th>( a )</th>
<th>( \beta )</th>
<th>( \eta )</th>
<th>( \nu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pads I(1)</td>
<td>10.3258</td>
<td>1.4116</td>
<td>2.2285</td>
<td>4.5391</td>
</tr>
<tr>
<td>Pads II(2)</td>
<td>12.7894</td>
<td>1.2511</td>
<td>2.1238</td>
<td>6.8399</td>
</tr>
<tr>
<td>Pads III(3)</td>
<td>3.6927</td>
<td>1.2509</td>
<td>1.6598</td>
<td>1.3568</td>
</tr>
</tbody>
</table>

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**Table II**

VALUES OF THE CONSTANTS FOR EQUATIONS (5), TEST TYPE 1, MATERIAL Tango Gray

<table>
<thead>
<tr>
<th>Specimen</th>
<th>( a )</th>
<th>( b )</th>
<th>( \eta_1 )</th>
<th>( \gamma_1 )</th>
<th>( \delta_1 ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pads IV(4)</td>
<td>1.6392</td>
<td>0</td>
<td>7.1294</td>
<td>1.0377</td>
<td>1.4</td>
</tr>
</tbody>
</table>

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Fig. 9. Experimental results for Pads I, Pads II, and Pads III; flattening vs. normal load (a) and relative stiffness calculated by using equation (2) (b).

Fig. 10. Experimental results for Pads I, Pads II, and Pads III; flattening vs. normal load (a) and relative stiffness calculated by using equation (4) (b).

Fig. 11. Experimental results for Pad IV; flattening vs. normal load (a) and model fitting using equation (5).
the pad deformation under an imposed displacement of 1.8 mm. Further details will be presented in a future publication.

VI. CONCLUSIONS

The reported preliminary experiments show that the proposed concept can work and is technologically feasible: design optimization is expected to allow the generation of purposely shaped load/deformation curves, with great help to the robotic limb designer who could plan distribution of local compliance according to the different functions and constraints of the various parts of the robot. This can be done without changing the adopted material, with great advantages in terms of continuity of the robotic limb surface. Many suggestions for future work are provided by the described experiments. Besides the necessary work to optimize the internal layer design and to customize its behaviour, other important functional effects must be investigated, like stiffness in tangential direction, shape recovery properties, energy dissipation and similar. However, we think that the most interesting perspectives are related to filling the communicating voids with a viscous liquid, thus adding better energy dissipation due to the transfer of liquid from deformed regions together with faster shape recovery with respect to the use of viscoelastic solid materials.

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REFERENCES