2010 IEEE International Conference on Robotics and Automation
Anchorage Convention District
May 3-8, 2010, Anchorage, Alaska, USA

Tailoring the viscoelastic properties of soft pads for robotic limbs through purposely designed fluid filled structures

Giovanni Berselli, Marco Piccinini and Gabriele Vassura

Abstract— **The majority of soft pads for robotic limbs studied so far were made by visco-elastic polymeric solids whose behavior is significantly influenced by the rate of application of the external loads or displacements. In particular, contact interfaces which are intrinsically visco-elastic are found, for instance, in human fingers and feet or in various robotic devices covered by a compliant surface. An outstanding instance are anthropomorphic hands where time-dependent phenomena profoundly affects the stability and sustainability of the grasp. Alternatively to homogenous solid pads, this paper proposes the use of fluid filled soft structures with differentiated layer design [1] that is the adoption of a single solid material, dividing the overall thickness of the pad into a continuous skin layer coupled with an internal layer having communicating voids. The voids are then hermetically sealed and, in case, filled with fluid. Given the allowable pad thickness, the purpose is to tailor the pad properties to the specific application by 1) selecting a skin material characterized by proper tribological features, 2) designing an inner layer geometry so as to obtain a specific static compliance, 3) filling the pad with a viscous fluid chosen so as to modify time-dependent phenomena and increase damping effects. The proposed concept is validated by designing artificial pads whose viscoelastic properties are either similar or more pronounced when compared to those of the human fingertip.**

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

I. Introduction

The interest in soft covers for robotic limbs is increasing primarily for three reasons, namely *acceptance* by the users, *safety* when interacting with the environment, and *functionality* in some specific tasks.

As to the *acceptance* by the user, a soft cover can be important in the case of robots that interact with humans (for instance rehabilitation devices) or humanoid robots in general. To this respect, an artificial skin with proper stiffness, consistency, color and shape can attenuate the impression of the robot as a machine, especially when dealing with particular groups of people like elderly or children.

As to *safety*, a soft cover can reduce the damage when accidently colliding an object [2]. The impact forces are indeed better distributed over larger contact areas. In addition, if the layer posses strong visco-elastic properties, it can enhance vibration damping.

As to *functionality*, the presence of a surface compliance can highly influence the performance of the robot when interacting with the environment during force/position controlled task, similarly to what happens in human fingers or feet which are covered by pulpy tissues. This last issue is particularly evident when considering end-effectors, covered by a visco-elastic pad, in contact with an object during grasping and manipulation tasks. This type of contact has been defined as visco-elastic contact [3]–[5] and includes a Time-Dependent (TD) response, due to relaxation or creep phenomena [6], [7], in addition to a Time-Independent (TI), non linear, elastic response. One can consider, for instance, the power law [8] or the exponential law [9] relation between the applied normal load and the contact deformation (displacement) at sufficiently high deformation rates [10]. Concerning the particular yet outstanding case of anthropomorphic hands [11], [12], the many benefits of surface compliance have been widely commented in the literature (see e.g. [13], [14], [15]). Considering first the TI properties at the contact interface, a local compliance allows shape adaption (conformability), large contact areas (with consequent reduced mechanical stresses and contact pressure), and the capability to exert torque normal to the contact plane [16]. Considering the TD properties, a visco-ealstic pads allows energy dissipation in case of shocks or vibrations, an increase in time of the contact area under a constantly applied load and an increase in time of the sustainable normal torque for a given surface friction (due to a better pressure distribution [3]). In practice the presence of an accurately designed visco-elastic pad can enhance grasp stability and sustainability [5].

More generally it is of paramount importance for the designer to tailor the pad properties to the specific application.

A. General aspect of soft pad design

The majority of soft pads for robotic limbs studied so far were made by visco-elastic polymeric solids homogenously shaped over an internal rigid core mimicking the bone or the robotic limb inner rigid structure. In such a case (as demonstrated in [12]), the parameters that mainly contribute to the pad compliance for a given external geometry are the layer thickness and the material hardness: an higher thickness signifies higher compliance which is beneficiary in terms

This research has been partially funded by the EC Seventh Framework Programme (FP7) under grant agreement no. 216239 as part of the IP DEXMART and by the Italian MIUR with the PRIN2007CCRNFA-004 (SICURA project).

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of safety and grasp stability/sustainability but detrimental in terms of overall limb dimension. On the other hand, an higher material hardness which is beneficiary in terms of surface reliability, signifies lower compliance. Usually the adopted pad design is a trade-off between the need of slender robotic limbs and good material properties. Concerning the pad TD properties, it is postulated [5] that the material display latency in response to external influences thanks to its microscopical structure (rearrangement of atoms, holes or polymeric chains); for a given thickness, materials with higher hardness (gel in Fig. 1) can display stronger visco-elastic properties when compared to softer material (silicone rubber) which can behave quasi-elastically.

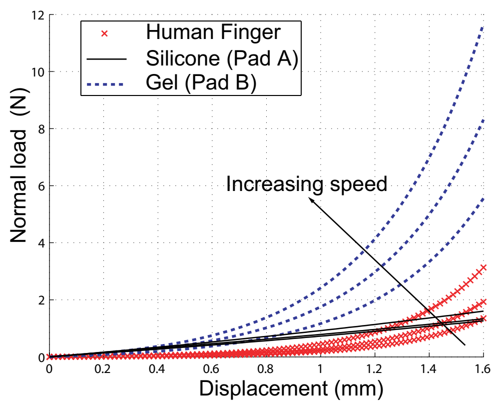


Fig. 1. Force response vs. indentation depth for human fingertip, silicone rubber (hardness 20 Shore 00, overall thickness 6mm) and polyurethane gel (hardness 40 Shore 00, overall thickness 6mm) at different velocities (0.1, 1, 100 mm/s respectively). Plot obtained by using a quasi-linear model with parameters obtained by numerical fit of experimental data. Model parameters are taken from [17] and [10].

Therefore, it is sometimes impossible to tailor the pad properties to the specific application by simply using an homogenous visco-elastic solid. As an example, consider the behavior of the human fingertip [9] which is similar to Pad A (made of silicone) in terms of compliance, somewhere in between Pad A and Pad B (made of gel) in terms of viscoelasticity, and harder than both Pad A and Pad B. Hence, considering the specific application of mimicking the human finger properties, it could be necessary to produce a multi-layer artificial pad with enhanced hardness, compliance and viscoelasticiy when compared to the mentioned homogenous pad shaped around a rigid core. In addition, if the pad needs to be used in robotic application, a lower thickness would be preferable.

Looking for alternative solutions to homogenous solid covers, the authors have previously proposed the concept of differentiated layer design (DLD) which allows to increase the pad compliance while minimizing its thickness. The concept of DLD consist in the adoption of a single solid 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). Differently from previously published solutions [14], [18], in the present work, the internal layer voids (which are purposely shaped so as to obtain a wanted compliance) are hermetically sealed and, in case, filled with an incompressible viscous fluid. Given the allowable pad thickness, the purpose is to tailor the pad properties to the specific application by:

- selecting a skin material characterized by proper tribological features (hardness),
- designing an inner layer geometry (Fig. 2) so as to obtain a specific static compliance (increased with respect to a non strucutured pad).
- hermetically sealing the inner layer voids and, in case, fill them with fluid so as to modify the TD phenomena (such as creep, stress relaxation, recovery time and energy dissipation).

A possible fluid-filled soft structures is presented and its behavior in contact conditions is characterized by experiments and described thorough a quasi-linear model [7]. Finally, the proposed concept is validated by designing artificial pads whose viscoelastic properties are either similar or more pronounced when compared to those of the human fingertip [9], [18]. These pads are intended to be used in anthropomorphic robotic hands which are expected to show similar potentials to those of the human hand in term of grasp stability and sustainability.

II. Design of soft pads with fluid filled structure

Figure 2 shows a soft pad with fluid-filled structure and DLD mounted on a rigid core. The fluid is hermetically sealed by means of girdles. The pad is composed of an external uniform layer with hemispherical geometry and an intermediate layer with fluid-filled voids. Similarly to the results reported in [19], the pad outer diameter is 20mm and its overall thickness is 3mm (dramatically reduced when compared to the results shown in Fig. 1). In fact, as stated above, the work reported in this paper is focused on the design of pads having shape and size compatible with application on the fingers of a safe robotic hand similar in size to a human hand (Dexmart European project and PRIN Sicura project).

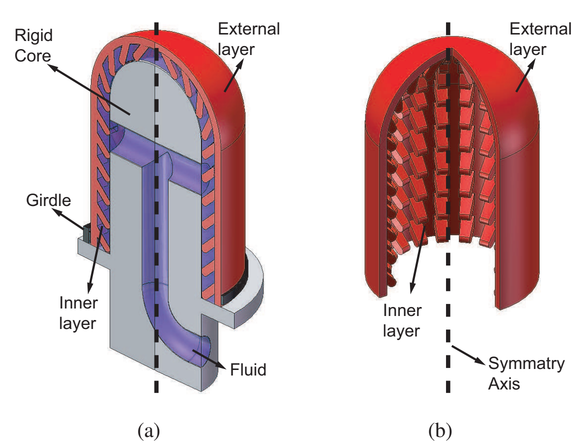


Fig. 2. Concept behind the proposed solution. 3D model (a), longitudinal cross section (b).

A. Selection of a skin material with proper hardness

Following the conceptual procedure outlined in Sec. 1., the design of the pad starts with the selection of a suitable solid with predetermined hardness. Two solutions have been considered:

- Silicone rubber Wacker ELASTOSIL RT 623 A/B: two-component silicone that vulcanizes at room temperature whose hardness can be varied in a very wide range by adding a third component (silicone fluid AK). Various pad geometries can be obtained through injection moulding.
- Tango Plus Fullcure 930 (hardness 27 Shore A): polymeric resin used for Rapid Prototyping. This stereo-litographic technique allows to get complex shape in a short producing time. Having a similar hardness to human thumb (about 25 Shore A) this material is chosen for the production of the pads.

Note that hyper-elastic constitutive laws (i.e. Ogden models [20]) for incompressible media have been used to describe the quasi-static behavior of both materials (see [21] for details). Therefore the Young modulus cannot be defined whereas the Poisson's coefficient is $\nu = 0.5$.

B. Design of the inner layer geometry

By using Rapid Prototyping or injection moulding, the intermediate layer can be obtained with various geometries with exception of closed-cell structures. In fact, concerning rapid prototyping, a removable wax must be deposited as a sustaining additional material in case of negative slope of the lateral surfaces. Concerning injection moulding the possible geometries are limited by the extraction of the mould. As widely commented in a previous paper [1], DLD represents an efficient way to alter the pad apparent stiffness at will of the designer. In addition (see [21] for details), design optimization through FEM can allow the generation of purposely shaped load/deformation curves. A possible geometry, which shows quasi-static behavior similar to that of the human finger, is depicted in Fig. 3 and it is composed of a pattern with a series of inclined micro-beams. Each

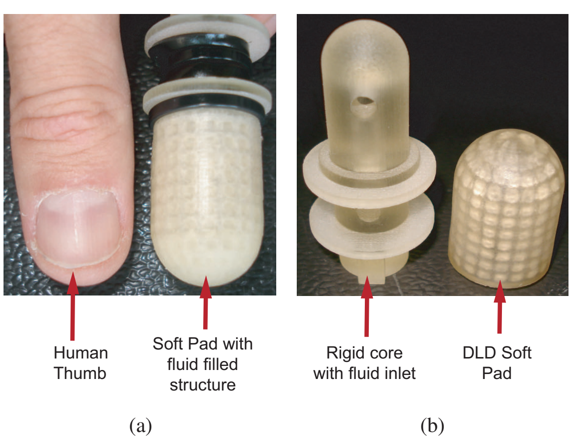


Fig. 3. Fluid filled soft Pad, comparison with human thumb dimensions (a), rigid core with fluid inlet (see Fig. 2(a)) and DLD soft Pad (see Fig. 2(b)) (b).

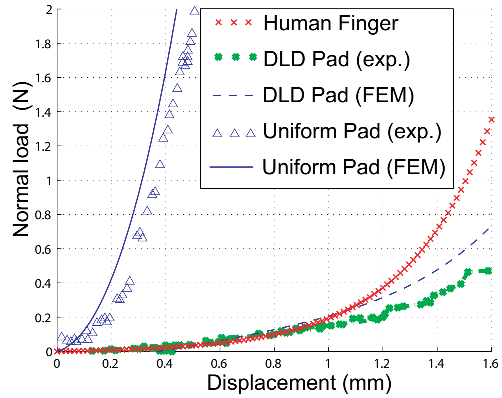


Fig. 4. Displacement (mm) versus normal load (N) for uniform Pad, DLD Pad and human fingertip (velocity of 0.1mm/s). Experimental (exp.) and FEM results.

beam connects the core to the external layer (skin) and it 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 beam. Figure 4 shows the experimental relationship between the normal load (N) and the resulting displacement (mm) for a uniform PAD and a DLD Pad (Fig. 3) made of Tango Plus. The pads are compressed against a flat rigid surface at a constant velocity of 0.1mm/s. The results are compared with numerical data obtained through FEM and with data concerning the human finger indented as described in [17]. It can be seen that a 3mm thick DLD pad represents a substantial step forward in human finger mimicry in terms of stiffness, when compared to previously published solutions where different materials and higher pad thickness are used. Hereafter, the DLD Pad will be referred to as Pad C.

C. Selection and integration of an incompressible viscous fluid

The soft pads are filled with an incompressible viscous fluid in order to alter their viscoelasticity. The addition of such fluid complicates the realization of the pad on one hand but enhances its TD properties (energy dissipation in case of shocks and vibrations, recovery time and grasp stability/sustainability in case of application on robotic hands). Differently from the use of a given viscoelastic solid, the proposed solution allows the robotic limb designer to modify the pad properties according to the different functions and constraints of the various parts of the robot while maintaining the same pad structure and dimensions (thickness). In [18] the pad viscoelasticity is varied by mixing a silicone gel base and an elastomer, though loosing the knowledge of the material mechanical properties each time the percentage of the constituent is changed. On the other hand, the prediction of the properties of a fluid-filled pad can be carried out by FEM analysis currently under development (which accounts for the fluid- structure interaction). Beside the use of simple DLD pad hermetically sealed (Pad C), two different fluid-filled pads are tested:

- Pad D: DLD pad filled with lubricant oil (viscosity $0.03 Nsec/m^2$ at 20°).
- Pad E: DLD pad filled with glycerin (viscosity $1.5 Nsec/m^2$ at 20°).

III. Experimental results and analysis

A. Experimental setup

Besides many properties and behavioral aspects that must be investigated for the characterization of a robotic pad, a primary role is played by the behavior of the pad under normal contact load in interaction with a rigid object. For each fluid, tests have been performed analyzing contact on the hemispherical end of the pad pressed against a rigid flat surface. The adopted experimental set up is visible in Fig. 5 and it is composed of a linear motor (Linmot P01-23x80) equipped with an high resolution position sensors ($1 \mu m$ is the maximum resolution), whose slider is directly connected with a load cell which supports a 35mm x 35mm flat rigid platen weighting 10g. A general purpose DSP-board is used to implement a basic position controller (with a sampling time of 1ms). In this way, proper trajectories are applied to the platen, that is pressed against the soft finger-pad imposing a controlled deformation. Through the load cell (characterized by a structural stiffness of 242.000N/mm, an overall weight of 11g, and accuracy of 0.1N) the normal component of the contact force is continuously monitored. The maximum acceleration imposed to the platen in all the experiments is about $1000 mm/s^2$ resulting in a maximum inertial force of 0.01N (reasonably neglecting the inertial effect due to the pad deformation). Inertial forces, which are not captured by the load-cell, are therefore disregarded.

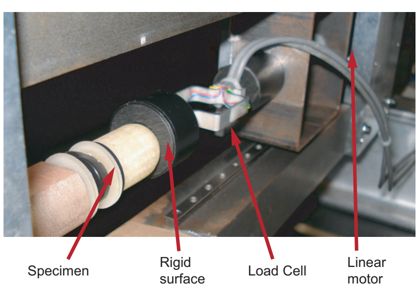


Fig. 5. A general view of the experimental set-up

The experimental analysis is performed by compressing the pad to a displacement of 1.6 mm using six different rates of loading (0.1, 1, 10, 20, 30, and 100mm/s), as demonstrated in Fig. 6 (results concerning 20, 30mm/s are omitted for clarity). The maximum displacement of the pad (1.6mm) is held constant for approximately 30s, allowing the response forces of the fingertip to stabilize. The platen displacement is then reduced to 0.80mm at a speed of 1.00mm/s, and the displacement (0.80mm) is held constant for another 30s.

B. Results and analysis

The pad viscoelastic behavior is analyzed using the simple and well known Fung's model in order to asses its applicability in the case of fluid-filled structures.

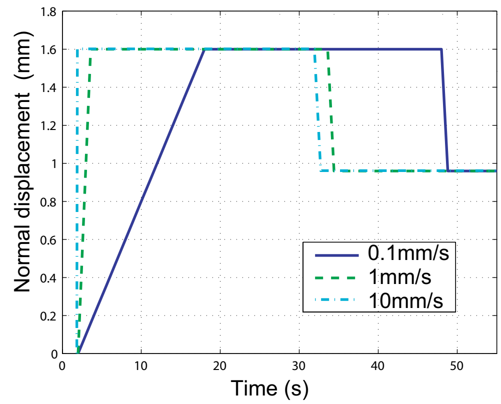


Fig. 6. The prescribed displacement histories of the compression platen.

In the general case the force response to a step change in displacement δ_0 (or, dually, the displacement response to a step change in force F_0) depends on time (t) as well as on the value of the step itself, i.e.

$$F(t) = \Psi(\delta_0, t) \quad (1)$$

$$\delta(t) = \Phi(F_0, t) \quad (2)$$

The functions Ψ (*relaxation function*) and Φ (*creep compliance*) depend, respectively, on the imposed displacement δ or force F as well as on the time t. Creep and relaxation phenomena are two aspects of the same viscoelastic behavior and are obviously related [6]. In order to compare to previously published results (Fig. 1) the following analysis studies the relaxation phenomenon following an imposed displacement. Nevertheless the same arguments apply if a force is applied and creep phenomena are investigated. In order to simplify the analysis, Fung [7] formulated the following form for the *relaxation function*:

$$\Psi(\delta, t) = F^{(e)}(\delta) \cdot g(t) \quad \text{with} \quad g(0) = 1 \quad (3)$$

where $F^{(e)}(\delta)$ is the *elastic response*, that is the amplitude of the force generated instantaneously by a displacement δ, while $g(t)$, called *reduced relaxation function*, describes the time-dependant behavior of the material. Considering the Fung's hypothesis, the force produced by an infinitesimal displacement $d\delta(\tau)$, superposed in a state of displacement δ at an instant of time τ, is, for $t > \tau$

$$dF(t) = \frac{\partial \Psi[\delta(\tau), t-\tau]}{\partial \delta} d\delta(\tau) \quad (4)$$

and, considering the Fung's hypothesis, expressed in (3), one achieves

$$dF(t) = g(t-\tau) \frac{dF^{(e)}[\delta(\tau)]}{d\delta} d\delta(\tau) \quad (5)$$

By applying a modified superposition principle, discussed in [6], [7], the total force at the instant t is the sum of the contribution of all the past changes, i.e.

$$F(t) = \int_0^t g(t-\tau)\ K^{(e)}[\delta(\tau)]\ \dot{\delta}(\tau) d\tau \quad (6)$$

where the term $K^{(e)}(\delta) = \frac{dF^{(e)}[\delta]}{d\delta}$ is the elastic stiffness and $\dot{\delta}(\tau)$ is the rate of displacement. The lower limit of the integral is zero (and not $-\infty$) assuming that the contact occurs at time $t = 0$ and $F^{(e)} = 0$, $\delta = 0$ for $t < 0$.
The relaxation function $g(t)$ is a decreasing, continuous function of the time, normalized to 1 at $t = 0$. It is composed by a linear combination (with the coefficient c_i depending on the material in homogenous structures) of exponential functions

$$g(t) = \sum_{i=0}^{r} c_i e^{-\nu_i \cdot t} \quad \text{with} \quad \sum_{i=0}^{r} c_i = 1 \tag{7}$$

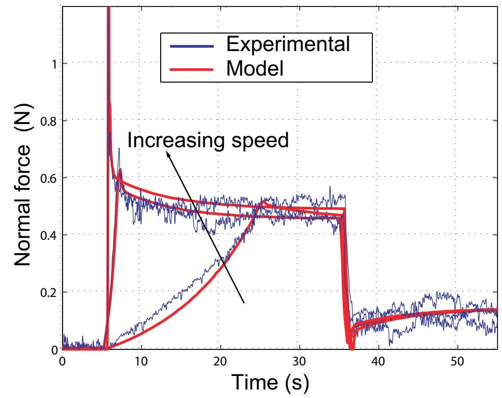
whose exponents ν_i identify the rate of the relaxation phenomena. Note that $\nu_0 = 0$. The number r and the value of such parameters depend on the behavior of the system under analysis. The value of ν_i and c_i are determined using the procedure outlined in [10].
The nonlinear elastic response $F^{(e)}(\delta)$ can be approximated by the force response in a loading experiment with a sufficiently high rate of displacement, without inducing shock waves. The force $F^{(e)}$ differs from the steady state response of the material for the constant c_0 and it can be modeled as:

$$F^{(e)}(\delta) = \frac{m}{b}(e^{b\delta} - 1) \tag{8}$$

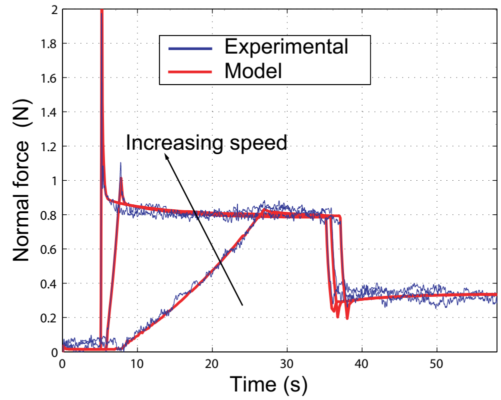
Let us consider a constant velocity indentation of the specimen starting at $t = 0$ with the pad barely touching the platen (uninflected configuration). From $t = 0$ to $t = t_0$, there is constant linear increase in displacement with slope γ (velocity of indentation). The total displacement at any time during the ramp is simply $\delta = \gamma t$. Thus, for this time frame (assuming Fung *reduced relaxation function*), the total force for $0 \le t \le t_0$ is given by:

$$\begin{aligned} F(t) &= \int_0^t \left(c_0 + \sum_{i=1}^{n} c_i e^{-\nu_i (t-\tau)} \right) \gamma m e^{b\gamma\tau} d\tau \\ &= \frac{m(\gamma c_0 e^{b\gamma t} - 1)}{b} + \sum_{i=1}^{n} \frac{m(\gamma c_i e^{b\gamma t} - e^{-\nu_i t})}{b\gamma + \nu_i} \end{aligned} \tag{9}$$

Equation 9 allows to obtain numerically the plot shown in Fig. 1 (coefficients from Table I).
Figure 7(a) shows experimental and numerical results for the DLD Pad filled with lubricant oil (Pad D) whereas Fig. 7(b) shows experimental and calculated results for the the DLD Pad filled with glycerin (Pad E). It can be seen that the well known Fung's model is capable of capturing the one-dimensional viscoelastic behavior of the fluid-filled pads proving that, even if the design can become more complicated when compared to a uniform pad, the modeling procedure (used in graps and manipulation control algorithm [14]) could remain unaltered.
Figure 8 shows the force response vs. indentation depth at different velocities (0.1, 1, 10, 100 mm/s) for the human fingertip (Pad H) and for the Pads C,D,E. Note that the effect of the lubricant oil is barely noticeable. A possible interpretation is that the presence of oil increases the pad viscosity on one side but decreases the friction of the inner layer micro-beams in contact with the rigid core. It can be seen that Pads C,D,E show a quasi-linear response. Nevertheless, if



(a)



(b)

Fig. 7. Force responses as a function of time for Pad D (a) and Pad E (b) subjected to the prescribed displacement histories as shown in Fig. 6 at different velocities (0.1, 1 mm/s, 30 mm/s respectively). Experimental results and model prediction.

compared to the solution of Fig. 1, Pad C and Pad D shows a behavior similar to that of the human fingertip whereas Pad E shows more pronounced visco-elastic properties. At last, numerical results for the model constants are reported in Tab. 1 for human finger and for Pad A,B,C,D,E. Work in progress includes 1) in-depth investigation of pad's compatibility with different type of tactile sensors 2)investigation of the properties of different incompressible fluids at varying temperature 3) detailed multi-physic Finite Element Analysis of the proposed designs.

IV. Conclusions

A novel soft visco-elastic pad based on the use of a fluid-filled structure has been presented along with an empirical methodology that allows to tailor the pad properties to the specific application. Preliminary experiments performed on artificial fingertips to be used on robotic hands shows that the proposed concept can work and is technologically feasible. In particular, when compared to previously published solutions, the proposed pad has several advantages namely 1) less overall thickness 2) predictable behavior 3) possibility to alter the pad properties without losing surface continuity and

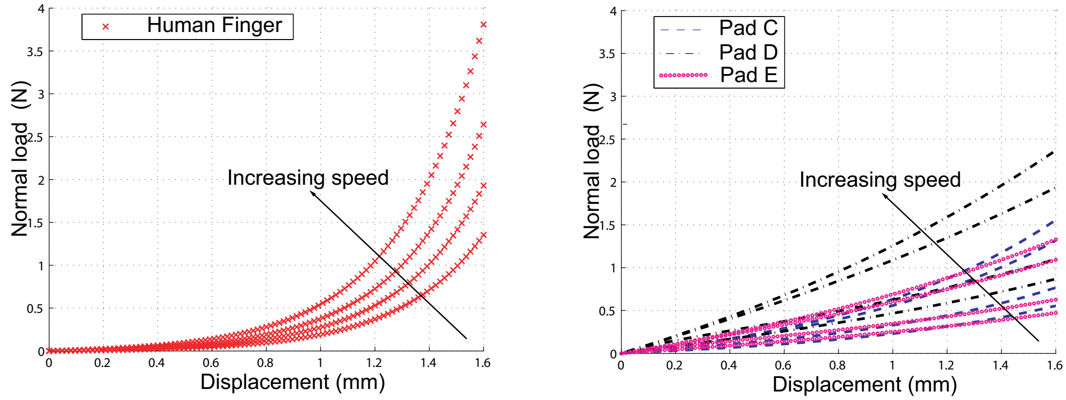


Fig. 8. Force response vs. indentation depth for human fingertip (left), Pads C,D,D at different velocities (0.1, 1, 10, 100 mm/s respectively). Experimental results and model prediction. Model parameters are shown in Tab. 1.

PAD	m	b	c_0	c_1	c_2	c_3	v_1	v_2	v_3
H	0.092	3.2	0.22	0.45	0.15	0.18	253	14	0.66
A	0.8068	0.267	0.7789	0.2211	0.202	0.18	3.1	0.33	0.66
B	0.5386	2.5147	0.358	0.44	0.202	0.18	4.14	0.33	0.66
C	0.518	0.577	0.3076	0.6200	0.0724	n	6.2350	0.1750	n
D	0.3400	1.1650	0.2955	0.6300	0.0745	n	6.2150	0.1400	n
D	0.9750	0.5190	0.3290	0.6300	0.0410	n	6.2150	0.1400	n

TABLE I

COEFFICIENT VALUES OF THE FUNG MODEL FOR HUMAN FINGER (H) AND PAD A,B,C,D.

adopted skin material. In this paper the fingertip behavior has been modeled (and predicted) through a simple one-dimensional model. Detailed multi-physic Finite Element Analysis of the proposed designs is currently in progress.

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