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# Linear Elastic Properties of the Facial Soft Tissues Using an Aspiration Device: Towards Patient Specific Characterization.

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1 **Linear elastic properties of the facial soft tissues using an aspiration device:**  
2 **towards patient specific characterization**

3

4 V. Luboz<sup>1</sup>, E. Promayon<sup>1</sup>, Y. Payan<sup>1\*</sup>

5 <sup>1</sup> UJF-Grenoble1/CNRS/TIMC-IMAG UMR 5525, Grenoble, F-38041, France, {vincent.luboz,  
6 Emmanuel.Promayon, ypayan}@imag.fr;

7

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9

10 \*Corresponding author:

11 Yohan Payan

12 Equipe GMCAO - Laboratoire TIMC-IMAG

13 Université Joseph Fourier - CNRS UMR 5525

14 Pavillon Taillefer

15 Faculté de Médecine - 38706 La Tronche cedex - France

16 Tel: +33 (0)4 56 52 00 01 - Fax: +33 (0)4 56 52 00 55

17 email: [Yohan.Payan@imag.fr](mailto:Yohan.Payan@imag.fr)

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22 **Abstract**

23 Biomechanical modeling of the facial soft tissue behavior is needed in aesthetic or maxillo-  
24 facial surgeries where the simulation of the bone displacements cannot accurately predict the  
25 visible outcome on the patient's face. Because these tissues have different nature and elastic  
26 properties across the face, depending on their thickness, and their content in fat or muscle,  
27 individualizing their mechanical parameters could increase the simulation accuracy. Using a  
28 specifically designed aspiration device, the facial soft tissues deformation is measured at four  
29 different locations (cheek, cheekbone, forehead, and lower lip) on 16 young subjects. The  
30 stiffness is estimated from the deformations generated by a set of negative pressures using an  
31 inverse analysis based on a Neo Hookean model. The initial Young's modulus of the cheek,  
32 cheekbone, forehead, and lower lip are respectively estimated to be  $31.0 \text{ kPa} \pm 4.6$ ,  $34.9 \text{ kPa} \pm$   
33  $6.6$ ,  $17.3 \text{ kPa} \pm 4.1$ , and  $33.7 \text{ kPa} \pm 7.3$ . Significant intra-subject differences in tissue stiffness  
34 are highlighted by these estimations. They also show important inter-subject variability for  
35 some locations even when mean stiffness values show no statistical difference. This study  
36 stresses the importance of using a measurement device capable of evaluating the patient  
37 specific tissue stiffness during an intervention.

38

39 Key terms: Soft tissues; Face; Mechanical parameters; Aspiration; Finite element method.

40

41

## 42 **1. Introduction**

43

44 In aesthetic and maxillo-facial surgery, most of the interventions are related to the  
45 bony structures and aim either at repairing functionalities of the oro-facial structures or  
46 improving their shape. To predict the final shape of the face after the displacement of the  
47 bones, most of the surgeons rely on their experience. Nevertheless, because of anatomical  
48 variations in the facial soft tissues, *i.e.*, in the amount of fat between the muscles, the  
49 thickness of the skin, or their material parameters, predictions may not always be accurate.  
50 Several research groups have presented simulators to help in the evaluation of the outcomes  
51 of aesthetic and/or maxillo-facial surgeries. For example, Chabanas et al.<sup>6</sup> presented a Finite  
52 Element (FE) model of the skull and face used as an atlas which can be deformed to fit the  
53 patient's anatomy. In this study, the soft tissues were modeled as a homogeneous, linear  
54 elastic material and its material parameters were chosen to fit a clinical case where pre- and  
55 post-operative CT scans were available. It led to a Young's modulus of 15 kPa, and a  
56 Poisson's ratio  $\nu$  of 0.49. Other finite element models also based on a linear modeling of the  
57 soft tissues have been presented in the literature<sup>3, 12, 14, 22</sup>. In these articles, the mechanical  
58 parameters were chosen either by comparing their simulation results with imaging data  
59 acquired from patients or were values from the soft tissue literature, although not specifically  
60 measured on the facial soft tissues. The validation of the predictions given by these simulators  
61 were therefore complicated by the fact that these mechanical parameters were either only  
62 representative of a single patient, or were not directly related to the facial soft tissues, or were

63 extracted from *ex vivo* measurements (and therefore might be different from *in vivo* because  
64 of the lack of perfusion and the difference of temperature<sup>13</sup>).

65 To improve the evaluation of these FE models, it seems important to be able to  
66 determine the material parameters of the facial soft tissues for a specific patient, or at least to  
67 give an accurate cartography of the face mechanical properties for an average patient, if  
68 possible. In a first attempt to reach this aim, an aspiration device, called the Cutometer  
69 (<http://www.courage-khazaka.de>)<sup>7, 18</sup>, was used to define several specific parameters such as  
70 immediate distension, delayed distension, immediate retraction, or final deformation of the  
71 face skin. These studies showed that viscoelastic properties are significantly influenced by  
72 aging. Unfortunately, in both studies, no clear link can be established between the Cutometer  
73 specific parameters and the more classical parameters used in mechanical constitutive laws.  
74 This device is mainly aimed at helping dermatologists in their need to quantify the elasticity  
75 in an aging trend more than for mechanical simulation purpose. Sonographic elastography has  
76 proven its ability to estimate the stiffness of soft tissues for maxillo-facial applications<sup>2</sup>. It  
77 provides a map of Young moduli for tissues' superficial layers which values can only be used  
78 for simulations assuming a small deformations framework. Other studies<sup>4, 5, 9, 15, 17</sup> tried to  
79 mechanically quantify the skin stiffness either by direct measurements or by using inverse  
80 methods to match deformations visualized on medical images. Unfortunately the initial  
81 Young's modulus (i.e., the initial slope of the stress-strain curve) and Poisson's ratio reported  
82 in these studies had fairly important ranges. For example, the Young's modulus was estimated  
83 by Bickel et al.<sup>5</sup> to 78 kPa and the Poisson's ratio to 0.47 using a Neo Hookean model. The  
84 Young's modulus was found to vary between 4 kPa and 18.8 MPa in *in vivo* and *in vitro*  
85 measurements according to Lapeer et al.<sup>15</sup>. Another study<sup>17</sup> also evaluated the initial Young's

86 modulus to 15 kPa using a Mooney Rivlin model (where  $C_{10} = 2.5$  kPa). In a previous study<sup>9</sup>,  
87 we evaluated the *in vitro* stiffness of the cheek of a fresh cadaver to 15 kPa. This work was  
88 done in the context of a maxillo-facial simulator. The skin initial Young's modulus was  
89 evaluated to 22.8 kPa using a Mooney Rivlin model (where  $C_{10} = 3.8$  kPa) and measurements  
90 on different locations on the face of one subject by Barbarino et al.<sup>4</sup>. In a recent study, a  
91 micro-robotic device was used by Flynn et al.<sup>8</sup> to record the force-displacement response of  
92 the cheek of five volunteers. Facial skin exhibits a non-linear, anisotropic, and viscoelastic  
93 force-displacement response. When modeled using an Ogden FE model, the skin initial  
94 Young's modulus was found to be between 15.9 kPa and 89.4 kPa. Flynn et al.<sup>8</sup> also showed  
95 variations in stiffness between different locations on the face for one subject. Such a paper  
96 stems questions about patient specific variations of the stiffness of the facial soft tissues and  
97 the stiffness variation depending on the location for different subjects.

98 In the present paper, we aim at clarifying these patient specific variations in order to  
99 improve the planning of different maxillo-facial surgeries using FE model. The objective is to  
100 provide a tool to evaluate the facial soft tissue stiffness (characterized here with the Young's  
101 modulus) while being compatible with the constraints of the operating room. The goal is to  
102 evaluate the *in vivo* initial Young's modulus for the facial soft tissues at four representative  
103 locations, namely the cheek, the cheekbone, the forehead, and the lower lip, and for a panel of  
104 subjects of different ages and body mass indexes. For the maxillo-facial application, a quasi-  
105 static framework can be assumed since boundary conditions corresponding to bone  
106 displacements are applied and simulated without taking into account the dynamic visco-  
107 elastic behavior of the soft tissues.

108

## 109 2. Materials and Methods

110

### 111 2.1 Aspiration technique

112

113 A device characterizing the mechanical behavior of the soft tissues was used to  
114 determine their initial Young's modulus. This device, called LASTIC (for Light Aspiration  
115 device for *in vivo* Soft Tissue Characterization), is based on the aspiration technique and was  
116 first introduced by Schiavone et al.<sup>19</sup> while quantifying the brain behavior<sup>20</sup>. This technique  
117 has also been used by Hollenstein et al.<sup>11</sup> for other applications such as the uterus or the liver.  
118 It also has been used on various *in vivo* tissues such as the forearm skin and the tongue<sup>21</sup>. In  
119 its current version, Figure 1, LASTIC is a 33 mm x 34 mm metal cylinder composed of two  
120 compartments. The lower one is an airtight chamber, open at the bottom by a 12 mm diameter  
121 circular aperture and closed at the top by a glass window. The upper compartment holds the  
122 electronic part consisting of a miniature 2 megapixel digital camera and a LED used as a light  
123 source. The aspiration chamber is connected to a programmable syringe pump that can  
124 generate a negative pressure (measured by a manometer) which deforms the tissues on which  
125 LASTIC is laid on. This deformation is imaged by the camera via a 45 degree inclined mirror  
126 which provides a view of the tissue from the side. The height of the tissue deformation is  
127 segmented on the recorded image. A basic camera calibration is performed to determine the  
128 pixel size. On average, the pixel size is around 0.01 mm. Measuring the deformation height  
129 corresponding to several steps of increasing negative pressures can give an estimation of the  
130 behavior of the tissues. LASTIC is fully sterilizable and can consequently be used inside the  
131 sterile fields of operating rooms.

132 The tissue measurements are then processed through an inverse analysis to estimate  
133 the tissue mechanical behavior. This analysis consists of matching the measured  
134 deformation/pressure curve to a pre-computed library of displacement heights determined by  
135 a FE Analysis of the aspiration experiment using a Neo-Hookean constitutive law<sup>1</sup>. Such a  
136 material is fairly stable and shows a behavior similar to the one simulated by Yeoh or  
137 Mooney-Rivlin materials at strains levels observed for such aspiration experiments. The Neo-  
138 Hookean equation is written as:

$$139 \quad W = C_{10}(I_1 - 3) + (J - 1)^2 / D \quad (1)$$

140 where  $I_1$  is the first invariant of the left Cauchy-Green deformation tensor,  $C_{10}$  is a material  
141 parameter,  $J$  is the determinant of the deformation gradient  $F$ ,  $D$  is a material  
142 incompressibility parameter (with  $D = (1 - 2\nu) / C_{10}$ ), and  $W$  is the strain energy. As in Chabanas  
143 et al.<sup>6</sup>, the skin is assumed to be nearly incompressible and a Poisson's ratio  $\nu$  of 0.49 was  
144 chosen. Note that, for small extensions (*i.e.*, in the linear elastic domain when  $I_1$  is close to 3)  
145 the initial Young's modulus, *i.e.*, the initial slope of the stress-strain curve, can be  
146 approximated by  $E = 6C_{10}$ .

147 The facial soft tissues are modeled by a thick circular slice while LASTIC is described  
148 by a rigid hollow cylinder (Figure 2). Taking advantage of the axisymmetric geometry of our  
149 model, the mechanical study is reduced to a two-dimensional structural analysis. The sample  
150 is meshed with approximately 2,000 linear quad elements. The mesh is refined in the  
151 neighborhood of the aspirated region, where highest deformation occurs, in order to increase  
152 the accuracy of the computed solution. The interface between LASTIC and the sample is  
153 specifically meshed with contact elements in order to ensure that the aspirated skin tissue  
154 slides without friction inside the LASTIC hole.



155           Given the different thicknesses of the studied facial tissues, an estimation of their  
156 variation was performed on a CT scan of a head (courtesy of subject #4). It presented a  
157 thickness of 5 to 6 mm for the forehead skin and of 15 mm or more for the tissues of the lip,  
158 cheek and cheekbone. To take this variation into account, two different axisymmetric models  
159 were used: one with a tissue thickness of 5 mm and one with a thickness of 15 mm (Figure 2).  
160 There was no need to create a model for each location over 15 mm because the maximal  
161 negative pressure created by LASTIC does not influence layers over 13 mm, see Figure 2. On  
162 the other hand, for the model with a tissue thickness of 5 mm, the maximal negative pressure  
163 created by LASTIC leads to a deformation of the tissues that is influenced by the tissue  
164 thickness. In this case, the maximum deformation measured in the tissues is around 13 %  
165 (assuming that we do not consider the specific region of contacts between the tissues and the  
166 LASTIC cylinder). For a tissue thickness of 15 mm, the maximum deformation is 17 %.  
167 These two values show that the material deformations are not too large; using a Neo Hookean  
168 model (thus neglecting the non-linearity due to very large deformations) is therefore relevant  
169 here.

170           The pre-computed library of displacements was generated using a wide range of  $C_{10}$   
171 and applied negative pressure for the two different thicknesses. Matching the measurements  
172 with the corresponding library (the 5 mm model for the forehead and the 15 mm model for the  
173 lip, cheek, and cheekbone), using a least-square minimization method, leads to an estimation  
174 of the  $C_{10}$  value corresponding to the tissue stiffness. This minimization is performed in less  
175 than a second.

176           The device has been validated in Luboz et al.<sup>16</sup> on several types of samples including  
177 silicone rubbers, with stiffness ranging from 10 kPa to 90 kPa, and compared to tensile tests.

178 This validation showed that LASTIC overestimates the stiffness by 16 % on average with a  
179 standard deviation of 9.5 %. This overestimation is mainly due to errors generated during the  
180 acquisition, namely due to the manometer precision and the camera calibration, which  
181 decreases the precision of the image segmentation to evaluate the tissue deformation.

182

## 183 2.2 Cartography of the face stiffness

184

185 To be able to improve the planning of the outcome of an aesthetic or maxillo-facial  
186 surgery, it is necessary to estimate the stiffness of the facial soft tissues in several places. Four  
187 locations with presumably different tissue thicknesses and different amounts of fat and muscle  
188 were consequently chosen: the cheek, the cheekbone, the forehead, and the lower lip. To  
189 study the possible variations between subjects, the stiffness estimation was performed on a  
190 group of 16 healthy subjects, eight males and eight females, of different ages and body mass  
191 indexes (mean age =  $29.2 \pm 6.3$ , mean BMI =  $21.5 \pm 2.1$ ). Subjects gave their informed consent  
192 to the experimental procedure as required by the Helsinki declaration (1964) and the local  
193 Ethics Committee (study agreement CERNI n°2013-11-19-30). LASTIC was used to estimate  
194 the stiffness of the soft tissues at these four locations for these 16 subjects, see Figure 3. Five  
195 measurements were performed for each location. In order to prevent the experimenter from  
196 applying too much pressure on the subject's skin with LASTIC and therefore creating a  
197 discomfort and a possible bias in the measurement, each subject was asked to place and to  
198 maintain LASTIC him/herself. The experimenter helped the subjects to reposition LASTIC as  
199 closely as possible to the previous location. The range of negative pressures applied at each

200 location varied for each subject. The initial negative pressure was 0 kPa while the maximal  
201 negative pressure was up to 7.3 kPa (= 73 mbar), depending on the subject and location.

202 To avoid any leaks at the interface between LASTIC and the tissues, a water wet  
203 gauze compress was used to wipe the skin before each measurement. This set up left a slight  
204 amount of water facilitating the suction and reducing the viscosity. Furthermore, LASTIC was  
205 very slightly pressed on the tissue by the subjects to ensure that the bottom compartment  
206 entire surface lies on the skin. The first three measured values were not used during the  
207 minimization process in order to compensate the initial load applied by the positioning of  
208 LASTIC, which could be observed as a bump on the video screen.

209 For each location, five measurements were made repeatedly: the first measurement  
210 was performed successively on the cheek, the cheekbone, the forehead, and the lower lip;  
211 then, the second measurement was performed successively on the cheek, the cheekbone, the  
212 forehead, and the lower lip, etc... until the fifth measurements was performed the same way.  
213 This repetitive cycle allowed the tissue of each location to relax between each measurement.  
214 A single measurement took about three minutes which means that overall, each subject's 20  
215 measurements were performed in about one hour.

216 During all the measurements, the subjects were asked to stay as relaxed as possible in  
217 order to keep the activations of the underlying muscles of the face as low as possible and  
218 consequently to reduce the impact of tissue anisotropy and initial tension on the  
219 measurements.

220

### 221 **3. Results**

222

223 The stiffnesses of the facial soft tissues (characterized here with the initial Young's  
224 modulus) measured with LASTIC on 16 healthy voluntary subjects at four locations, as well  
225 as the sex, age and BMI of each subject, are shown in Table 1. The cheek, cheekbone,  
226 forehead, and lower lip mean stiffnesses of each subject, as well as the standard deviation  
227 resulting from the five measurements at each location, are given in the four last columns. The  
228 overall subjects' mean stiffness for each of the four locations is also given on the bottom row.  
229 The corresponding initial Young's modulus are  $E_c = 31.0 \text{ kPa} \pm 4.6$  for the cheek,  $E_{cb} = 34.9$   
230  $\text{kPa} \pm 6.6$  for the cheekbone,  $E_f = 17.3 \text{ kPa} \pm 4.1$  for the forehead, and  $E_l = 33.7 \text{ kPa} \pm 7.3$  for  
231 the lower lip. Neither tissue stiffening nor softening is observed for the repeated  
232 measurements; we therefore assume that there is probably little influence of the pre  
233 conditioning.

234 The complete measurements are given in the supplementary material. Figure 4  
235 presents a Whisker box plot showing the mean, minimal and maximal initial Young's modulus  
236 (in kPa) for the cheek, cheekbone, forehead and lower lip. The result of the bilateral paired  
237 Welch's T-test between the forehead and the three other locations is also presented. This test  
238 is an adaptation of the Student's t-test intended for use with two samples having possibly  
239 unequal variances<sup>23</sup>.

240 Table 2 shows the results of a bilateral paired Welch's T-test between each  
241 measurement location. The p-value resulting from this test demonstrates that the difference  
242 between the mean stiffness of the forehead  $E_f$  and the cheek  $E_c$  ( $p=2.5E-5$ ) is statistically  
243 significant ( $p \leq 0.05$ ). This is also significant for the difference between  $E_f$  and  $E_l$  ( $p=7E-6$ )  
244 and for  $E_f$  and  $E_{cb}$  ( $p=1E-6$ ). On the other hand, there are no statistical differences between  $E_c$   
245 and  $E_l$ , between  $E_c$  and  $E_{cb}$ , and between  $E_l$  and  $E_{cb}$ .

246 It is to be noted that the evaluated mean stiffnesses do not show any dependence  
247 neither with the age, BMI or sex.

248 Nevertheless, subject to subject differences can be observed for each location even if  
249 there is no overall statistical difference. It is the case for example for the cheekbone and lower  
250 lip stiffness of subjects #5 and #15:  $E_{cb}(5) = 22.1$  kPa and  $E_l(5) = 33.3$  kPa while  
251  $E_{cb}(15) = 35.1$  kPa and  $E_l(15) = 22.3$  kPa. Another example of the disparity can be seen  
252 between subjects #10 and #12 for the cheek and lower lip stiffness:  $E_c(10) = 37.1$  kPa and  
253  $E_l(10) = 28.0$  kPa while  $E_c(12) = 31.6$  kPa and  $E_l(12) = 45.7$  kPa. These two subjects have  
254 completely different stiffness values compared to the mean stiffness  $E_l$  for the lower lip (it can  
255 be observed that  $E_l(10) = E_l \times 83\%$  while  $E_l(12) = E_l \times 135\%$ ), see Figure 5, and for the cheek  
256 while overall there is no statistical difference between these two locations ( $p=0.424$ ). For all  
257 these values, the standard deviations for the five measurements used to obtain these mean  
258 values are relatively low (between 4.0 and 7.9 kPa).

259

#### 260 **4. Discussion**

261

262 The stiffness values presented in Table 1 and Figure 4 and outlined in the previous  
263 paragraph show fairly important variations between subjects, even if there is no statistical  
264 difference over the whole subject pool. The cheek stiffness measured on all the 16 subjects  
265 fall within the range given by Flynn et al.<sup>8</sup> (which is based on cheek measurements on five  
266 volunteers): from 15.9 kPa to 89.4 kPa.

267 As shown in Table 2, the stiffnesses of the forehead and the cheek, of the forehead and  
268 the lower lip, and of the forehead and the cheekbone are statistically different. It can be

269 explained by the smaller tissue thickness (and different boundary conditions) for the forehead  
270 as compared to the cheek, the lower lip, and the cheekbone. Precisely measuring tissue  
271 thicknesses at different locations (with MRI or US imaging) should help in understanding  
272 more deeply these differences. Measuring and estimating variations in tissue types or muscles  
273 activations should also provide some clues to explain the observed differences.

274 A first estimation of facial tissue stiffness can nonetheless be given with our LASTIC  
275 measurements. For a given location, the inter-subject variability can be estimated by the  
276 standard deviation  $sd(E_i/E)$ , where  $E_i$  is the normalized Young moduli of subject  $i$  and  $E$  is the  
277 average Young modulus of all  $E_i$ . The inter-subject variability  $sd(E_i/E)$  is equal to 27 %, 29  
278 %, 29 %, and 27 %, respectively for the forehead, cheek, lower lip, and cheekbone. For a  
279 given location, the intra-subject variability can be estimated by the average standard deviation  
280  $mean(sd(E_{i,j}/E_i))$ , where  $E_{i,j}$  is the resulting measured Young modulus for the measurement  $j$   
281 of subject  $i$ . The intra-subject variability  $mean(sd(E_{i,j}/E_i))$  is equal to 22 %, 16 %, 21 %, 19 %,   
282 respectively for the forehead, cheek, lower lip, and cheekbone. This shows that for a given  
283 location, the intra-subject variability (i.e., the standard deviation per subject) is smaller than  
284 the inter-subject variability (i.e., the standard deviation per location). Consequently the small  
285 variation of position due to the repositioning of the device between two measurements for the  
286 same location has less effect on the estimation than the change of stiffness from a subject to  
287 another. Furthermore, we could question the fact that muscle activation could play a role in  
288 the estimation of the stiffness since two locations include muscles that can be voluntarily  
289 activated (i.e., lip and forehead) while the other two include muscles that are more difficult to  
290 activate voluntarily (i.e., cheek and cheekbone). The lower lip and forehead have indeed  
291 higher inter-subject variability than the cheek and cheekbone. Finally, it is important to note

292 that the maximal difference between location variability being 6 % (between forehead and  
293 cheek), these variations could also be explained by a change of device positioning, or a  
294 measurement error (see our previous work<sup>15</sup> for an estimation of LASTIC errors).

295 The stiffness differences pointed out in the last part of the results section illustrate the  
296 fact that even if there is no statistical difference over the whole subject pool between some  
297 locations, for example between cheekbone and lower lip, there are fairly important variations  
298 of the stiffness between subjects. For example, it would be inaccurate to take the mean value  
299  $E_{cb} = 34.9$  kPa for the cheekbone for subjects #4 and #13 while the measured stiffness values  
300 were evaluated to  $E_{cb}(4) = 50.7$  kPa and  $E_{cb}(13) = 51.6$  kPa, which would correspond to an  
301 underestimation of 30%. The same observation can be made for the stiffness of the lower lip  
302 in subject #8: the mean value  $E_l = 33.7$  kPa while the subject's stiffness value was estimated  
303 to  $E_l(8) = 17.9$  kPa; this would lead to an over-estimation of 88%. It therefore seems essential  
304 in the context of FE model for surgical planning to take these inter-subject variations into  
305 account.

306 Two types of limitations should be considered for this study: the first one concerns the  
307 experimental set up, and the second one concerns the mechanical set up. The experimental set  
308 up has four main limitations: the fact that muscle activation is not recorded during the  
309 experiments, the assumption that the facial soft tissues are homogeneous, the assumption that  
310 those tissues exhibit a linear stress-strain response, and the low variation of the subject pool in  
311 terms of age and BMI. The main limitation is relative to muscle activation. Even though  
312 subjects were asked to be as relaxed as possible, we cannot guarantee that their muscles were  
313 not activated at all, which would consequently have biased the measurements by stiffening the  
314 tissues. Because this activation could not be measured without using invasive EMG sensors, it

315 is likely that the measurements with high standard deviation are the consequence of  
316 involuntary muscle activation.

317 Assuming that the facial soft tissues are homogeneous is also erroneous: they are  
318 composed of several layers of skin (including epidermis, dermis and hypodermis), muscles  
319 and fat and can be more than a centimeter thick. Given the level of aspiration generated by  
320 our LASTIC device (never higher than 7.3 kPa and a maximum tissue bump of about 5.1 mm,  
321 with a maximal pre-load of 3.2 mm, leading to an actual deformation directly due to the  
322 suction of 1.9 mm), the obtained characterization is mainly limited to the superficial layers of  
323 the facial tissue (epidermis and dermis), few millimeters below the skin at most. Assuming  
324 that these tissues are homogeneous consequently results in a non-completely accurate  
325 stiffness estimation. The stiffness estimation could be improved by considering a  
326 heterogeneous model with several layers of tissues with different mechanical properties. For  
327 instance, a two layer model including a thin superficial layer for the skin and a thicker one for  
328 the underlying tissues could be considered as a better approximation of the face tissues.  
329 Measuring the facial soft tissue stiffness in their full thickness would also need a higher level  
330 of negative pressure, which would probably have been refused by the Ethics Committee  
331 because of the risk for generating pain or damaging the tissues.

332 Assuming that the facial soft tissues exhibit a linear stress-strain response is also  
333 inaccurate for large deformations: because of their heterogeneity, the tissues mainly have a  
334 nonlinear response<sup>9</sup>. Estimating the Young's modulus corresponding to a Neo Hookean  
335 constitutive law is consequently accurate only for the initial low strain stiffness. Using a more  
336 complex constitutive law, such as one derived from a Mooney Rivlin or Ogden formulation,  
337 would probably improve the accuracy of the stiffness estimation with LASTIC.



338 Finally, despite some individual differences, the relatively small variations of the  
339 stiffness measured on our group of subjects can be explained by its low variance in age and in  
340 BMI. The subjects being all young or relatively young (between 23 and 44) their skin is likely  
341 to be in good shape and fairly elastic. As for the subject's BMI, it ranges between 16.8 and 26,  
342 and only four subjects are outside the standard deviation range [19.4; 23.6]. Most of the  
343 subjects therefore have probably a small amount of fat tissues under their face skin. The  
344 studied group is consequently not extremely representative of the world population neither in  
345 age nor in BMI.

346 Three main limitations can be listed concerning the mechanical set up: the low level of  
347 negative pressure generated by LASTIC, the initial load that may have been applied on the  
348 soft tissues, and the possible inaccuracy or non-reproducibility of the position of the  
349 measurements on each subject.

350 As stated above, the level of aspiration generated by LASTIC is never higher than 7.3  
351 kPa which therefore limits the estimation of the stiffness to only superficial tissues. Using  
352 higher negative pressures could help to quantify deeper tissues but could also injure the  
353 subject; this was consequently not performed in our study.

354 Another source of inaccuracy in the stiffness estimation is due to the fact that the  
355 initial load applied on the soft tissues at the beginning of each measurement (to avoid any  
356 leaks) is not simulated in the FE model nor used for the inverse analysis. Removing the first  
357 three measured values seems a reasonable approximation as it is assumed that the pressure  
358 compensates the initial load and the consequent deformation of the tissues<sup>15</sup>. The initial load  
359 is always kept below the precision threshold of the manometer by checking the measured  
360 pressure on the manometer and the camera image. The degree of this initial pressure applied

361 by the subjects is controlled during and after the experiments. This initial load creates an  
362 initial deformation of the tissues and a light aspiration has consequently no influence on them.  
363 Once the pressure is strong enough to aspirate the tissues, the tissue deformation is visible on  
364 the camera image. This threshold was reached around the third pressure step. Nevertheless,  
365 this compensation is not accurate and might lead to a deviation of the stiffness value.

366 The inaccuracy of the location of the measurements for each subject could also be  
367 responsible for increasing the resulting variance. The experimenter visually estimates the  
368 positioning error to a maximum of 5 mm; we therefore assume that this has a minimal effect  
369 on the stiffness evaluation.

370

## 371 **5. Conclusion**

372

373 A map of the stiffness of the facial soft tissues is presented in this paper as measured  
374 by LASTIC, a device based on the aspiration technique. Using an inverse analysis with a FE  
375 Neo Hookean behavior, it provides an estimation of the stiffness of the tissues at four  
376 locations: the cheek, the cheekbone, the forehead and the lower lip. On average, the stiffness  
377 coefficient of the soft tissues composing the cheek, the cheekbone, the forehead, and the  
378 lower lip are respectively estimated to be 31.0 kPa, 34.9 kPa, 17.3 kPa, and 33.7 kPa.  
379 Considering all measurements, it seems difficult to obtain and use values describing an  
380 average patient. With statistical differences between the forehead and the cheek ( $p=2.5E-5$ ),  
381 between the forehead and the lower lip ( $p=7E-6$ ) and between the forehead and the cheekbone  
382 ( $p=1E-6$ ), this study shows that the tissue thickness as well as the amount and nature of fat  
383 tissues and muscles below the skin probably play a role in the stiffness. Although no

384 dependences can be exhibited between the mean tissue stiffnesses and neither the age, the  
385 BMI nor the sex of the subjects, this study gives an interesting first insight in the variation of  
386 the stiffness between subjects at different locations on the human face. The inter-subject  
387 variations appearing in our measurements are pointing out that *in vivo* patient specific  
388 measurements are essential to accurately model the facial soft tissues and that an average  
389 stiffness value is not adequate for a patient specific model. Specifically designed small  
390 aspiration devices are a convenient and practical way for doing so. As LASTIC can be  
391 sterilized, it could be used routinely during clinical practice in order to assess rapidly the  
392 patient specific tissue stiffness during the planning of aesthetic or maxillo-facial surgeries.

393 Future works will aim at correcting the limitations of this study. Firstly, the range of  
394 the population tested with LASTIC should be broaden by measuring the stiffness of the  
395 tissues on younger and older subjects and with a larger variation in BMI. Secondly, the  
396 accuracy and reproducibility of the device positioning during the measurements could also be  
397 improved, for instance by marking precisely onto the skin the aspiration locations. Increasing  
398 the level of negative pressure that LASTIC can generate in order to quantify the stiffness of  
399 deeper tissues is also possible but can only be done after evaluating the risk of damaging the  
400 skin. Quantifying the properties of the different skin layers and underlying tissues could also  
401 be implemented by using different sizes of orifice for the suction similarly to the work of  
402 Hendricks et al.<sup>10</sup>. Another improvement to be addressed is the fact that following only the  
403 deformation of one point at the top of the tissue aspired dome is not enough to evaluate soft  
404 tissues' anisotropy. We therefore plan to segment the whole deformation dome from the  
405 acquired images and to measure its possible asymmetries which could lead to study the  
406 tissues' anisotropy. Lastly, monitoring the muscle activation might be possible using surface

407 EMG, even though it might be difficult to avoid the electrodes placed close to LASTIC, thus  
408 interfering with the aspiration device.

409

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414 Ethical approval: This study was conducted according to the principles expressed in the  
415 Declaration of Helsinki and all participants gave their written informed consent. Ethical  
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418 especially his help to design LASTIC and the process to estimate the stiffness modulus.

419

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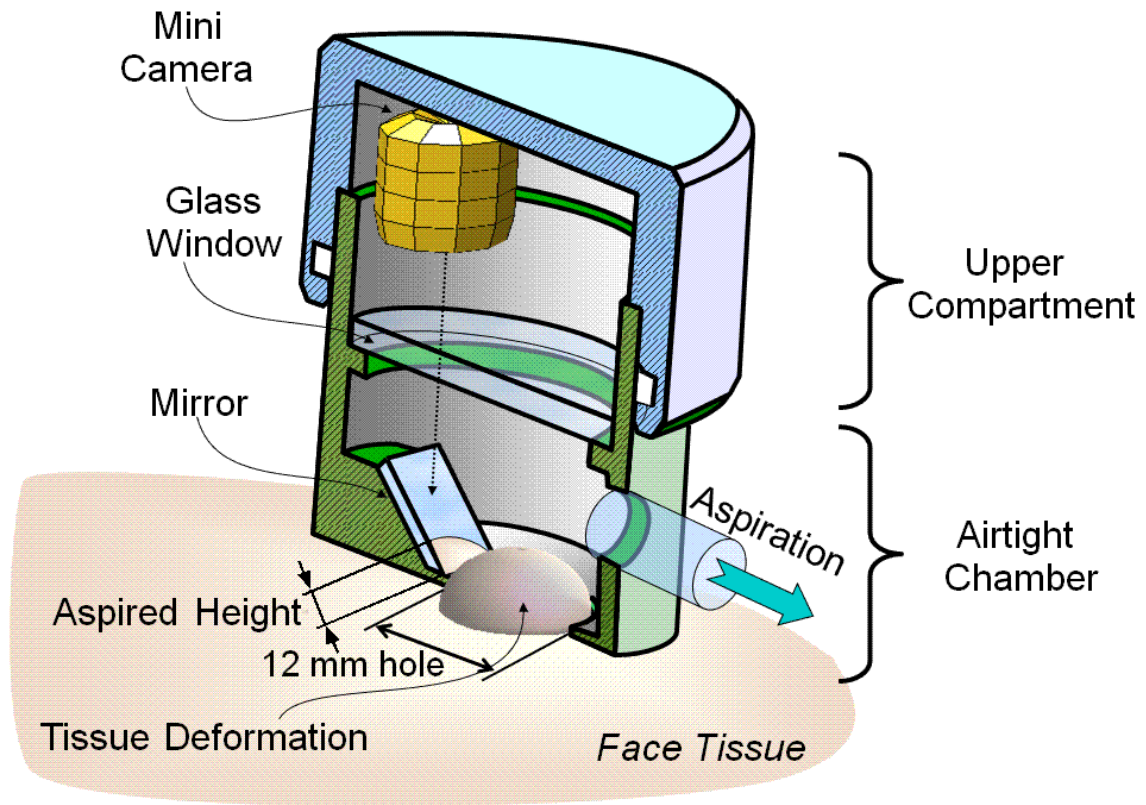
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485 Figures and tables

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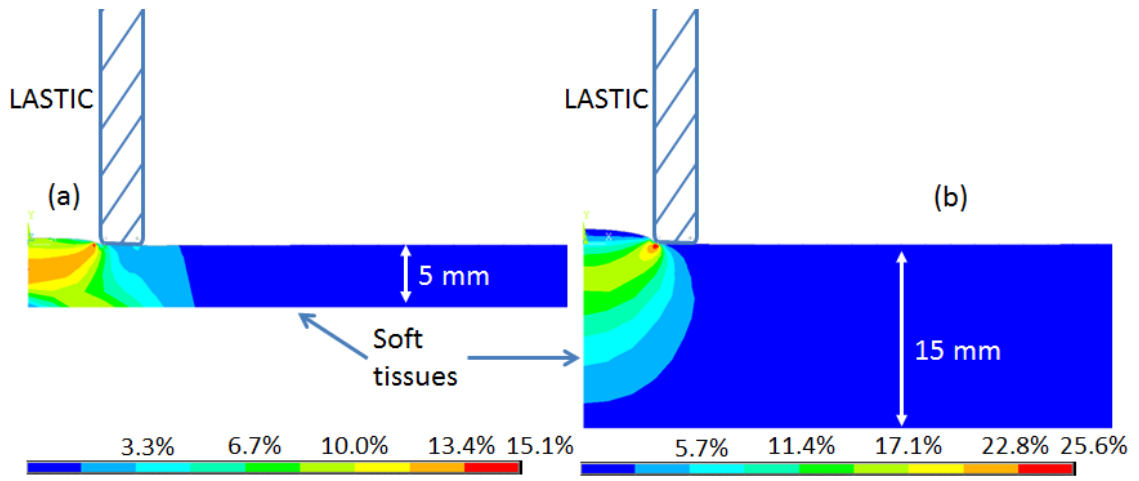
487 Figure 1 Luboz



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489 Figure 2 Luboz



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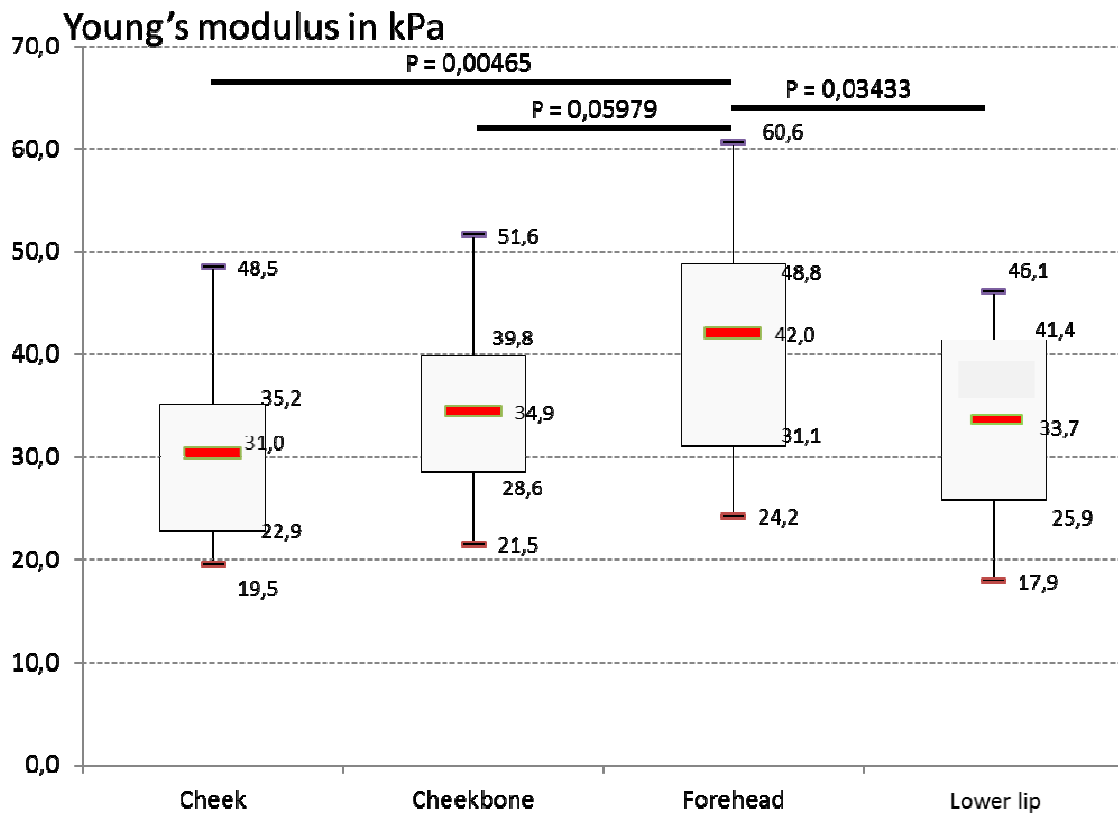
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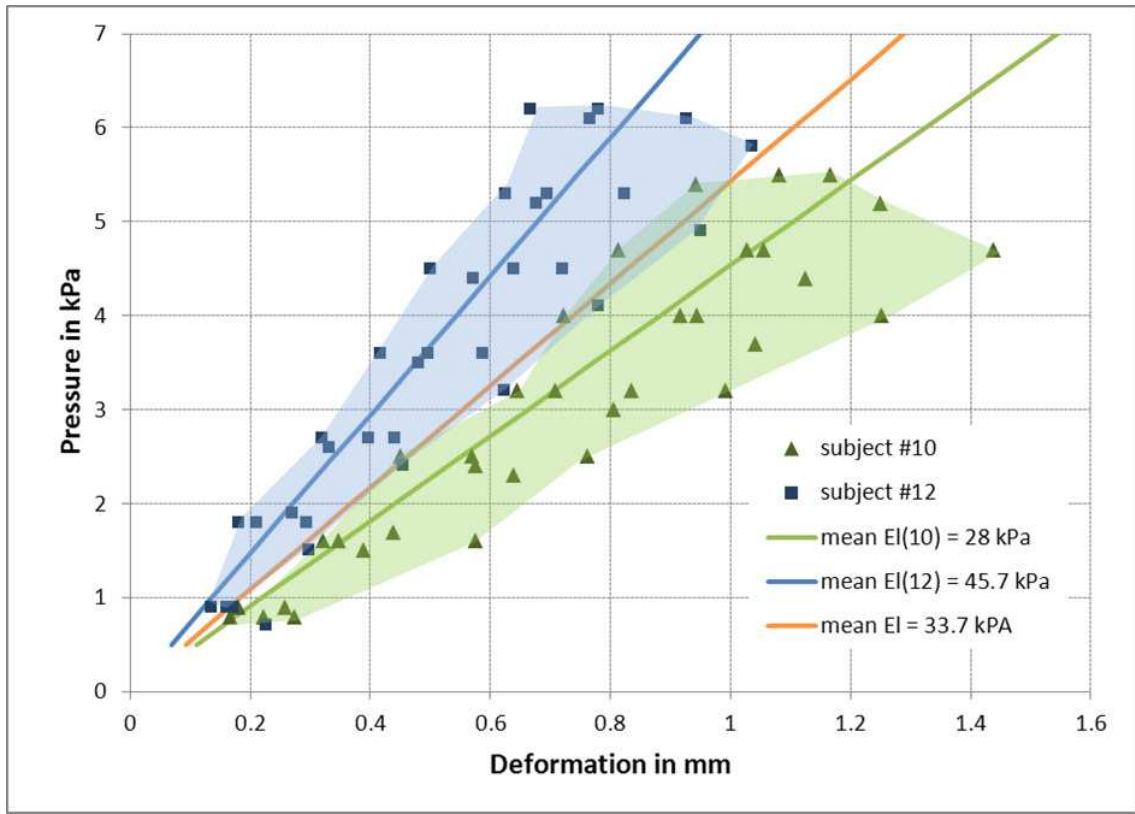
495 Figure 4 Luboz



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498 Figure 5 Luboz



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500 Table 1 Luboz

Subject # / sex	age (years)	BMI (kg.m <sup>-2</sup> )	Cheek E <sub>c</sub> (i) ± std (kPa)	Cheekbone E <sub>cb</sub> (i) ± std (kPa)	Forehead E <sub>f</sub> (i) ± std (kPa)	Lower lip E <sub>l</sub> (i) ± std (kPa)
1 / M	44	22.0	21.3±3.7	21.5±2.1	10.6±1.6	19.1±3.4
2 / M	35	21.2	20.7±4.5	23.1±3.4	9.9±2.4	20.1±4.1
3 / F	26	20.7	23.4±7.4	29.0±11.8	16.0±2.7	46.1±12.7
4 / F	35	22.8	48.5±9.9	50.7±5.0	24.2±7.4	41.2±7.2
5 / F	26	19.2	21.1±5.0	22.1±2.5	10.5±2.9	33.3±8.2
6 / M	23	21.1	28.9±3.3	32.1±2.8	13.0±2.9	27.1±7.2
7 / F	24	20.3	34.5±4.6	39.3±13.8	30.2±7.9	36.5±7.9
8 / M	23	21.9	19.5±2.3	27.3±6.6	11.7±3.5	17.9±4.6
9 / M	39	26.0	31.2±4.0	41.4±5.8	18.9±3.8	39.8±11.4
10 / F	24	16.8	37.1±4.9	39.3±10.9	19.5±5.1	28.0±5.9
11 / M	27	25.1	29.1±3.3	39.1±10.1	22.8±1.8	38.0±11.9
12 / M	27	19.9	31.6±4.0	30.5±8.1	24.8±6.6	45.7±7.9
13 / M	27	22.1	43.1±2.6	51.6±7.5	15.9±4.1	42±12.8
14 / F	32	21.5	44.5±3.7	42.4±3.7	21.9±7.5	39.1±3.8
15 / F	32	21.2	29.5±3.3	35.1±1.0	15.6±2.9	22.3±1.0
16 / F	24	22.3	32.4± 7.0	33.7± 11.0	11.5±2.9	43.4± 6.3
Mean	29.3±6.		E <sub>c</sub> =	E <sub>cb</sub> =		
± std	3	21.5±2.1	31.0±4.6	34.9±6.6	E <sub>f</sub> = 17.3±4.1	E <sub>l</sub> = 33.7±7.3

501 Table 2 Luboz

	Cheek $E_c$	Lower lip $E_l$	Cheekbone $E_{cb}$
Forehead $E_f$	0.000025	0.000007	0.000001
Cheek $E_c$		0.424	0.238
Lower lip $E_l$			0.733

502 Captions:

503 *Figure 1 – Cross section of LASTIC’s two compartments. The lower part is the aspiration*  
504 *chamber with the mirror and the upper part contains the camera that images the deformation.*

505 *Figure 2 – The two different Finite Element models used to create the precomputed library*  
506 *of displacement heights / pressure curves, for a tissue thickness of (a) 5 mm (forehead), and*  
507 *(b) 15 mm or more (lip, cheek, cheekbone). The Von Mises strains are plotted on both sides,*  
508 *showing maximum deformations (of (a) 15 % and (b) 26 %) near the interface with LASTIC*  
509 *because of the contact. But the measured displacement height is at the top of the deformation*  
510 *dome.*

511 *Figure 3 – The measurements are done at four locations: the cheek, the cheekbone, the*  
512 *forehead, and the lower lip. The subjects are asked to position and hold LASTIC themselves*  
513 *under supervision of the experimenter. From the LASTIC measurements, the stiffness of the*  
514 *facial soft tissues at the different location can be estimated.*

515 *Figure 4 – Whisker box plot showing for each location: mean, minimal and maximal initial*  
516 *Young's modulus (in kPa). The result of the bilateral paired Welch's T-test between the*  
517 *forehead and the three other locations is also presented.*

518 *Figure 5 – Variation of the initial Young's modulus  $E_l$  (lower lip) for subjects #10 and #12*  
519 *(averaged for the five measurements), compared to the mean initial Young's modulus for all*  
520 *subjects. The mean stiffness computed by the inverse analysis using a Neo Hookean*  
521 *approximation is also plotted (continuous lines). Measurement points are also plotted.  $E_l(10)$*   
522  *$= E_l \times 0.83$  and  $E_l(12) = E_l \times 1.35$ .*

523 *Table 1 – Age, body mass index (BMI), sex (M for Male and F for Female), initial Young's*  
524 *modulus  $E$  (in kPa) and standard deviation (std) of each subject  $i$  for the facial soft tissues at*  
525 *four locations: cheek ( $E_c$ ), cheekbone ( $E_{cb}$ ), forehead ( $E_f$ ), and lower lip ( $E_l$ ).*

526 *Table 2 – P-value for each possible pair of locations where the stiffness is estimated.*

527

528

529