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The role of hairs in the adhesion of octopus suckers: a hierarchical peeling approach

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Abstract

Organisms like the octopus or the clingfish are a precious source of inspiration for the design of innovative adhesive systems based on suction cups, but a complete mechanical description of their attachment process is still lacking. In this paper, we exploit the recent discovery of the presence of hairs in the acetabulum roof of octopus suction cups to revise the current model for its adhesion to the acetabulum wall. We show how this additional feature, which can be considered an example of a hierarchical structure, can lead to an increase of adhesive strength, based on the analysis of the cases of a simple tape and an axisymmetrical membrane. Using peeling theory, we discuss in both cases the influence of hierarchical structure and the resulting variation of contact angles on the adhesive energy, highlight how an increase in number of hierarchical levels contributes to its increase, with a corresponding improvement in functionality for the octopus suckers.

1. Introduction

The *Octopus vulgaris* is one of the most intelligent animals that lives on Earth. It uses its suckers to perform many functions ([1], [2]). In particular, octopus suckers are able to generate a maximum pressure difference of about 0.27 MPa that can be reached in a few milliseconds [3]. Other animals, such as clingfish, exploit suction cups with a bed of microfibrils or "micropapillae", which are tiny soft protuberances that line the cup perimeter, to better adhere to rough rock surfaces underwater [4]. For this reason, these structures represent a remarkable source of inspiration for designing artificial suction cups or adhesives ([5]–[8]). To develop these artificial devices, the full

understanding of the adhesion process and the capability to model it correctly is crucial. In the past, octopus suckers and their interaction with the substrate have been studied mainly by analyzing their arrangement [9] and structure ([10], [11]). In Tramacere et al.[9], a method to identify the suckers in the octopus arm was developed in order to better determine its mechanics through imaging. Moreover, in Tramacere et al. [10], three techniques (MRI, ultrasonography, and histology) were used to gain a 3D reconstruction of the sucker (Fig. 1). In this context, the acetabulum protuberance in the acetabulum cavity was discovered for the first time. Experimental studies were also performed to measure the full mechanical properties of the octopus sucker tissues in [11]. Unfortunately, a reliable value of the Poisson ratio remains to be obtained. Work is in progress to resolve this issue. The adhesion of the octopus suckers is achieved by exploiting the pressure difference between the external environment, the acetabulum cavity and the infundimbulum cavity (Fig. 1a) [12]. To maintain this pressure difference, the acetabulum roof and the acetabulum wall must remain in full contact [10]. More in detail, at the initial stage of adhesion, the infundimbulum is the first part of the sucker in contact with the substrate to form a seal. Then, the acetabular radial muscles contract to reduce the internal pressure in the sucker with respect to the external one. Finally, the meridional muscle of the acetabulum contracts to achieve contact between the acetabulum roof and the acetabulum cavity. At this point, all muscles are contracted. When they relax, the adhesion is maintained by the adhesive force maintaining the two surfaces in contact (the acetabulum roof and the acetabulum cavity) [13]. Morphological studies show that the latter does not present any hairs and can be considered flat.

As in other bioadhesion problems, peeling theory has been adopted to describe how these two parts of the octopus suckers delaminate [14]. The first elastic approach developed in the literature in this respect was the Kendall model [15], which describes the peeling of a thin elastic tape from a rigid substrate. The main physical quantity that governs the attachment, or the detachment, of the tape is the surface energy γ, which is defined as the energy required to generate a unit area of interface (for a certain crack speed), with Mode I (opening) primary separation mode. In the Kendall model, the force necessary to detach the membrane can be determined by adopting an energy-based criterion, imposing the Griffith's balance between the elastic energy, the adhesive energy and the work of the applied load [16]. The peeling force relative to a tape pulled at an angle θ, is thus:

$$F = Etw \left(\cos \alpha_0 - 1 + \sqrt{(1 - \cos \alpha_0)^2 + \frac{2\gamma}{Et}} \right) \qquad (1)$$

65 where E is the Young's modulus of the tape, t its thickness and w its width. Introducing $\hat{F} =$

66 $F/(Etw)$, where Etw represents the force necessary to generate a unit strain in the tape, and $\hat{\gamma} =$

67 $\gamma/(Et)$, the relation can be written in non-dimensional form:

68 $$\hat{F} = cos\,\alpha_0 - 1 + \sqrt{(1 - cos\,\alpha_0)^2 + 2\hat{\gamma}} \qquad (2)$$

69 Starting from this approach, a series of more refined models were developed in order to describe

70 various biological mechanisms of adhesion. Among these, the theory of multiple peeling was

71 introduced to model a system of numerous tapes loaded by a single force at a common point [17].

72 This was used in complex adhesive systems, e.g. to describe the adhesive behaviour of spider web

73 anchors [18],[19],[20]. Effects such as tape geometry, viscoelasticity or surface roughness [21], [22]

74 have also been considered, as well as bending stiffness[23]. Moreover, a so-called "hierarchical

75 shear lag model" was introduced to model hierarchical contact splitting occurring in biological

76 adhesive structures such as gecko pads [24], [25], which are suitable for active dynamic short-term

77 attachment, and other approaches have considered the effect of pretension in hierarchical

78 structures [26]. These works showed that hierarchical structuring of the surface also leads to the

79 reduction of stress concentrations and the appearance of multiple separate peeling fronts, with a

80 resulting increase in adhesive capabilities. These examples indicate the possibility of exploiting

81 various types of structures present in nature for enhanced adhesion in artificial adhesives.

82 The recent discovery of the presence of hairs in the acetabulum roof of the octopus' suckers [27]

83 (Fig. 1) suggests a revision of the model outlined in Tramacere et al. [13]. In particular, the peeling

84 model therein can be improved by adding the additional effect due to the presence of hairs on the

85 flat membrane. This work therefore aims to model the peeling process of a membrane equipped

86 with hierarchical hairs, i.e. to analyse how the hairs affect the peeling force. To do this, we apply

87 Yao's approach [28] to the geometry of an axisymmetric membrane, formulating a modified

88 expression for the work of adhesion as a function of the surface energy in a hierarchical structure

89 and deriving the corresponding detachment force of the membrane.

90

91 **2. Theoretical model**

92 *2.1 Hierarchical tape with hairs*

93 We analyse a simple tape with hairs at the interface with the substrate, as shown schematically in

94 Fig. 2, which we define as "hierarchical", meaning that its adhesive properties depend on structures

95   present at two (or more) different size scales. As a first approximation, hairs are considered to be

96   of the same material of the tape (an incompressible soft material with $v = 0.5$). Furthermore, they

97   are modelled as flat tapes of thickness t_1, width w_1 detached length L_1 and contact length l_1. The

98   distance between two adjacent hairs is ρ along both x and y directions, so that $N = lw/\rho^2$ is the

99   total number of hairs. The hairs form an angle α_1 with the substrate that is considered to be

100 constant, and whose relation to the tape contact angle α_0 is discussed below. During the attachment

101 and detachment phases, we do not consider bunching effects of the hairs and possible variation

102 effects in the section of the tape. Equation (1) is valid for a simple tape without hairs. The presence

103 of hairs on the tape surface results in an increase of the equivalent surface energy, since there is

104 additional elastic energy stored in the hairs themselves that is "dissipated" as kinetic energy

105 released after detachment ([25], [29]). Thus, Eq. (1) remains valid and the surface energy term can

106 be modified to

107
$$\gamma' = \gamma + \gamma_H \qquad (3)$$

108 where γ' is the total surface energy, γ the surface energy of the flat tape and γ_H the equivalent

109 surface energy due to the additional elastic energy stored in the hairs. As a first approximation, we

110 neglected the roughness of the substrate. According to previous work [22], this roughness is not

111 expected to influence results significantly, unless it is of the order of the microscopic features (i.e.

112 the hairs) of the adhesive surface, which is not the case considered herein.

113 Since all hairs are assumed identical, γ_H can be considered homogeneous over the whole contact

114 surface, and can be evaluated as:

115
$$\gamma_H = \frac{l_1 + L_1}{2Ew_1^2 t_1 l_1} \ P_1^2 \quad (4)$$

116 where P_1 is the detachment force of a single hair. Using Eq. (1) to compute P_1 , we obtain:

117
$$\gamma_H = \frac{Et_1}{2}\left(1 + \frac{L_1}{l_1}\right)\left(\cos\alpha_1 - 1 + \sqrt{(1 - \cos\alpha_1)^2 + \frac{2\gamma}{Et_1}}\right)^2 \quad (5)$$

118 We can now write Eq. (3) in non-dimensional form:

119
$$\hat{\gamma}' = \hat{\gamma} + \frac{\gamma_H}{Et} = \hat{\gamma} + \frac{t_1}{2t}\left(1 + \frac{L_1}{l_1}\right)\left(\cos\alpha_1 - 1 + \sqrt{(1 - \cos\alpha_1)^2 + \frac{2t}{t_1}\hat{\gamma}}\right)^2 \quad (6)$$

120 Substituting this expression for the surface energy in Eq. (2), we obtain the modified non-
121 dimensional pull-off force as:

122 $$\hat{F} = cos\,\alpha_0 - 1 + \sqrt{(1 - cos\,\alpha_0)^2 + 2\hat{\gamma} + \kappa_1 \left(cos\,\alpha_1 - 1 + \sqrt{(1 - cos\,\alpha_1)^2 + \lambda_1\hat{\gamma}}\right)^2} \quad (7)$$

123 Where $\kappa_1 = \frac{t_1}{2t}\left(1 + \frac{L_1}{l_1}\right)$ and $\lambda_1 = \frac{2t}{t_1}$. Equation (7) thus represents the dimensionless force

124 necessary to detach a rectangular tape equipped with hairs. Notice that the area fraction, i.e. the

125 ratio between the contact areas of the tape with/without hairs, respectively, is usually considered

126 close to 1, i.e., the presence of hairs does not entail a reduction/increase of the contact area[25].

127 To illustrate the resulting behavior, we plot the peeling force $\hat{F}$ in Fig. 3b for various angles ϵ, having

128 chosen the following parameters: $\hat{\gamma} = 4 \cdot 10^{-4}$, $w = 10^{-2}m$, $l = 10^{-2}m$, $t = 10^{-3}m$, $w_1 = 10^{-5}m$, $l_1 =$

129 $10^{-5}m$, $L_1 = 10^{-5}m$, $t_1 = 10^{-5}m$. As expected, the presence of a hierarchical structure, i.e. of

130 hairs, contributes to an increase of the adhesive properties of the tape for all peeling angles due to

131 the additional stored elastic energy, which is dissipated during delamination, with an increased

132 effect for small angles. The peeling force decreases only slightly for increasing ϵ values. For $\alpha_0 = 0$,

133 and $\alpha_1 = 0$, the tape is sheared parallel to the surface, and the additional dissipated energy due to

134 the contribution of the hairs is maximum. Conversely, their decreasing effect when the peeling angle

135 increases and tends to $\pi/2$ is consistent with the qualitative behavior observed in biological

136 adhesion, where the peeling force needs to be maximized mainly for small peeling angles, while

137 facilitated detachment is required at larger angles, to achieve the ON/OFF mechanism necessary,

138 e.g. for motion in animals like geckos or insects like beetles.

139 It should be noted that in Eq.(1) and its derivations, we neglect the effect of the deformation of the

140 substrate. In previous work, the presence of a soft substrate in peeling problems was seen to give

141 rise to an overall increase in the detachment force, due to a wider load distribution at the interface,

142 reducing the load concentration at the peeling line, and a decrease of the local peeling angle [22].

143 Thus, we expect the soft substrate not to affect the predicted qualitative behavior.

144

145 *2.2. Hierarchical axisymmetric membrane*

146 The detachment of a single octopus' sucker can be treated as the peeling of an axisymmetric

147 membrane [13], treated by Afferrante et al. [30], and schematically illustrated in Fig. 4a. The non-

148 dimensional force necessary to detach the membrane is

149 $$\hat{F} = \left(\frac{32}{27}\right)^{\frac{1}{4}} (\hat{\gamma})^{\frac{3}{4}}(1 + \hat{a}) \qquad (8)$$

where $\hat{F}$ and $\hat{a}$ are the dimensionless normal load and detached radius, respectively. Equation (8) predicts a linearly increasing peeling force with the membrane detached radius $\hat{a}$, i.e. an adhesive membrane can ideally bear an arbitrary load, provided it is large enough. In this case, the modification of γ due to the presence of hairs should be also considered. By inserting Eq. (6) in Eq. (8) we obtain the non-dimensional force necessary to detach the axisymmetric membrane equipped with hairs, although in this case the latter are assumed to be radially distributed, as shown in Fig. 4b. Making the same assumptions as in the previous Section, we obtain the detachment force of the axisymmetric membrane as:

$$\hat{F} = \left(\frac{32}{27}\right)^{\frac{1}{4}} \left(\hat{\gamma} + \kappa_1 \left(\cos\alpha_1 - 1 + \sqrt{(1-\cos\alpha_1)^2 + \lambda_1 \hat{\gamma}}\right)^2\right)^{3\backslash 4} (1+\hat{a}) \qquad (9)$$

The role of the hairs for the axisymmetric membrane can be visualized in Fig. 5. In this case, we plot the peeling force versus the detached radius $\hat{a}$ for $\hat{\gamma} = 4\cdot 10^{-4}$, and various values of α_1. The dependence is linear, but again, the presence of a hierarchical structure implies a considerable increase in the adhesive properties of the membrane for a given detached radius. The influence of the hairs on the peeling force decreases as the angle increases, but the $\hat{F}$ vs. $\hat{a}$ curves remain considerably larger than that relative to non-hierarchical case, even for large angles, e.g. $\alpha_1 = 0.4$. This is again consistent with the qualitative behavior observed in biological adhesion, where the peeling force needs to be maximized mainly for small peeling angles.

It should be noted that in Eq.(1) and its derivations, we neglect the effect of the deformation of the substrate. In previous work [22], the presence of a soft substrate in peeling problems was seen to give rise to an overall increase in the detachment force, due to a wider load distribution at the interface, reducing the load concentration at the peeling line, and a decrease of the local peeling angle. Thus, we expect the soft substrate not to affect the predicted qualitative behaviour.

2.3 Additional levels of hierarchy

The previous model can be extended to additional levels of hierarchy, as illustrated schematically in Fig. 3a. In this case, Eq. (3) can be extended as follows:

$$\gamma' = \gamma + \gamma_1 + \gamma_2 + \cdots + \gamma_n \qquad (10)$$

where γ_1 coincides with the previously introduced γ_H. The total force necessary to detach this type of tape/membrane can be computed as previously, by recursively adding the terms relative to the

179   appropriate hierarchical level. For example, the second level of hierarchy can be described by adding

180   to $\hat{\gamma}_1$ another term of the form

$$\hat{\gamma}_2 = \kappa_2 \left(cos\,\alpha_2 - 1 + \sqrt{(1 - cos\,\alpha_2)^2 + \lambda_2 \hat{\gamma}} \right)^2 \qquad (11)$$

182   where κ_2 , λ_2 and α_2 are analogous to the first level parameters κ_1, λ_1 and α_1, respectively.

183   Analogous expressions can be written for $i > 2$. In order to compute the κ_i and λ_i and α_i parameters,

184   it is necessary to consider the geometry (i.e. geometry and contact angles at the various hierarchical

185   levels) of the new system. The approach outlined in the previous sections can then be adopted to

186   determine higher order surface energy values γ_i to the adhesive energy due to the additional

187   hierarchical levels, and the corresponding peeling force. Given the small bending stiffness of the

188   tapes at the various hierarchical levels, the angle variations from one hierarchical level to the next

189   are in all cases small. Therefore, the corrections decrease in magnitude for an increasing number of

190   levels, i.e. the adhesive energy and force values do not diverge. This can be seen in results illustrated

191   in Fig. 6. Here, we consider as previously a perturbation ϵ on the contact angle from one level to the

192   next, and assume for simplicity that the perturbation is of the same order for each level, i.e.

193     $cos\,\alpha_{i+1} = cos(\alpha_i + \epsilon)$, $\forall i$. Thus, an increase of the hierarchical level also implies an increase in

194   the overall perturbation on the initial peeling angle α_0. Figures 6a and 6b show the effect of an

195   increasing number of hierarchical levels for the $\hat{F}$ vs. α_0 and $\hat{F}$ vs. $\hat{a}$ plots in the case of a hierarchical

196   tape and a hierarchical axisymmetric membrane, respectively. For 3 levels of hierarchy, at $\alpha_0 = 0.1$

197   the adhesive force is increased by approximately 6 times with respect to the non-hierarchical case.

198   It is apparent that the main increase takes place for the first hierarchical levels, as is clearly visible

199   in Figs. 6c and 6d, where $\hat{F}$ is plotted as a function of the number of hierarchical levels for fixed θ

200   and $\hat{a}$ values, again in the case of a hierarchical tape and a hierarchical axisymmetric membrane,

201   respectively. We can compute the gain in adhesive force at level i by dividing F_i by the force at level

202   i-1 (F_{i-1}).

$$Gain = \frac{F_i}{F_{i-1}} \qquad (12)$$

204   Plotting the gain values versus the hierarchical level for the simple tape and the axisymmetric

205   membrane (Fig. 6 e, f), we see that after 2 or 3 levels, there is no further significant gain. Therefore,

206   we can state that 2 or 3 hierarchical levels are sufficient to optimize adhesive force. A further

207   increase in hierarchical levels could be detrimental, since the smallest features would become of

208   the order of the characteristic size of the substrate roughness, leading to a decrease of adhesion

209 [22]. This is consistent with observations on biological adhesive structures found in nature, such as

210 beetle legs or gecko toes [16][31], which typically display 2 or 3 levels of hierarchy. In the case of

211 octopus's sucker membranes, hairs appear to be present at most at three levels of hierarchy.

212

213 **Conclusions**

214 Understanding of the effect of a layer of hairs on the adhesive properties of octopus' suckers is

215 important for the design of artificial suction cups with improved adhesion for various applications,

216 such as smart-skin attachable skin patches [32] or biorobotic adhesive discs [33]. Here, we have

217 evaluated the effect of hierarchical structure, i.e. the presence of hairs, on the adhesion and

218 detachment of a simple tape and of an axisymmetric membrane, in order to gain insight into the

219 adhesion mechanism of octopus' suckers (in particular the detachment of the acetabulum roof from

220 the acetabulum wall). The model is based on a number of simplifying assumptions, e.g. that there is

221 no hair bunching and that the peeling angle does not vary significantly between structures at one

222 hierarchical level and those at the next. Furthermore, delamination is assumed to take place from a

223 rigid substrate, whereas the real biological tissue considered is soft and relatively deformable.

224 However, these assumptions are not expected to qualitatively modify the analysis herein.

225 Results for the simple tape case indicate that the presence of hairs can improve the adhesive

226 properties by more than 30% at small peeling angles, with the effect decreasing for larger angles.

227 This is consistent with observations on biological adhesion, where typically adhesive forces need to

228 be enhanced at small peeling angles. The main parameter determining this increase is the initial

229 detached length of the hairs, which has an upper limit in lengths for which there is an onset of

230 bunching effects. The detachment force for an axisymmetric membrane also increases in the

231 presence of hierarchical structuring. We show that the model can be easily extended to the analysis

232 to multiple levels of hierarchy. Here, results indicate that the first hierarchical levels are the ones

233 that contribute more to an increase in adhesive force. In terms of convergence, we find that after

234 the third level of hierarchy there is no longer a significant change in peeling force.

235 This paper provides a possible explanation for the role of the hairs in octopus' suckers, correctly

236 accounting for their role in determining the ON/OFF behavior during adhesion. Currently, further

237 studies are under way to evaluate other possible functions of these hairs (e.g. sensing) that could

238 be fundamental to the octopus functionality. Our work can also help the design of artificial suction

239 cups by providing a model that predicts the potential benefits of a hierarchical surface in terms of

240 improved and angle-dependent adhesive properties.

252 **Author Contributions**

253 N.M.P designed the study and supervised the work, G.G. wrote the first draft of the manuscript and

254 generated diagrams supervised also by F.B.. All the authors finalized the manuscript.

255 **Additional Information**

256 **Competing Interests:** The authors declare that they have no competing interests.

257 **Data availability:** The authors declare that the data supporting the findings of this study

258 are available within the article and its supplementary information files.
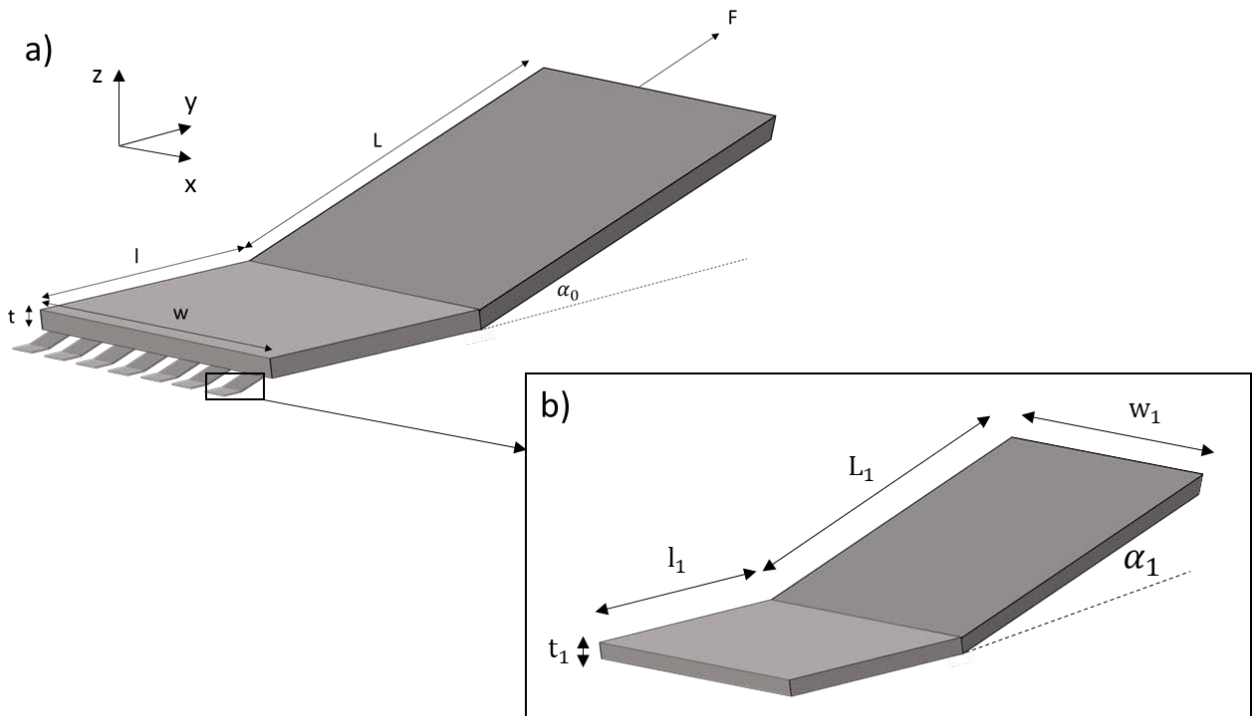
259
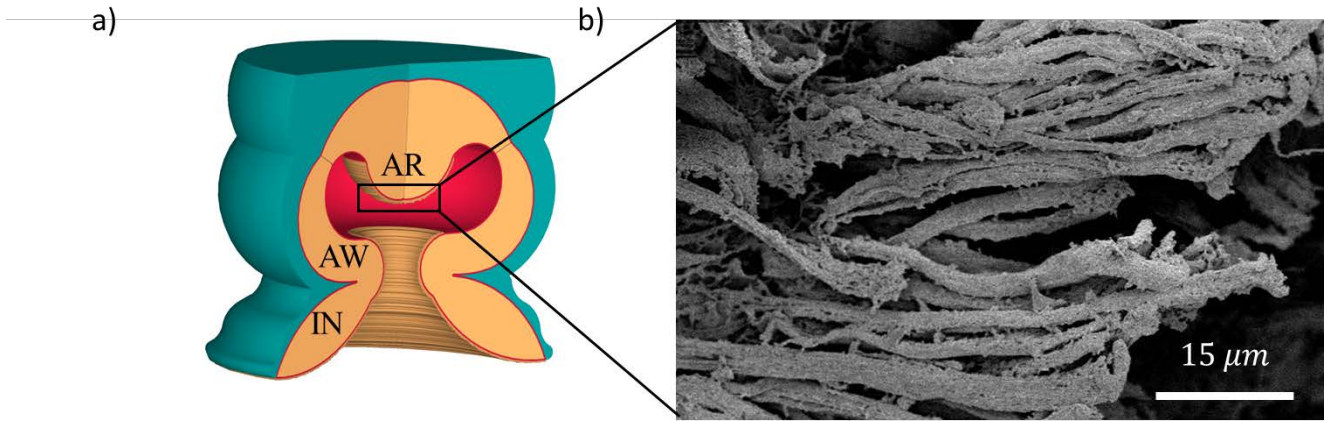
Figure 1: a) Schematic of the octopus' sucker: Acetabular Roof (AR), Acetabular Wall (AW) and Infundibulum (IN). b) Hairs present on the surface of the AR that is attached to the AW during adhesion.
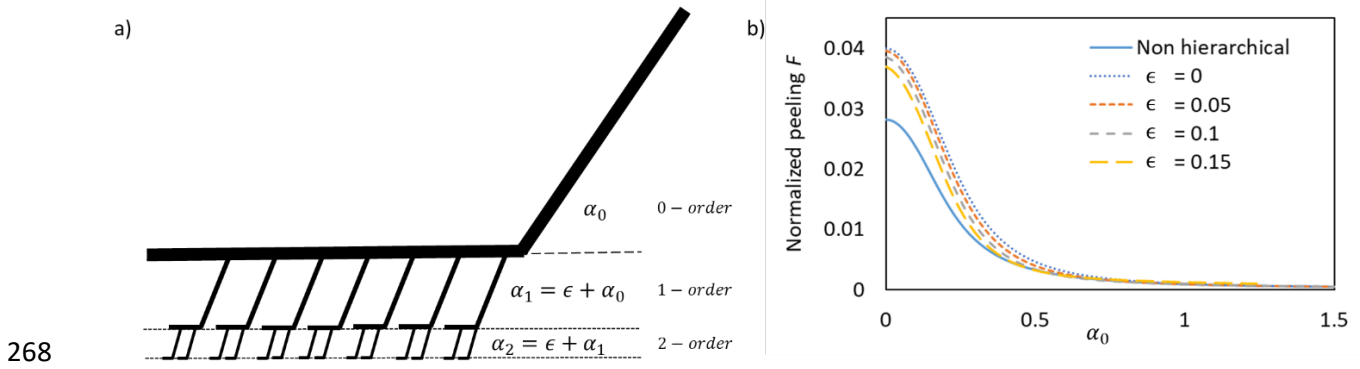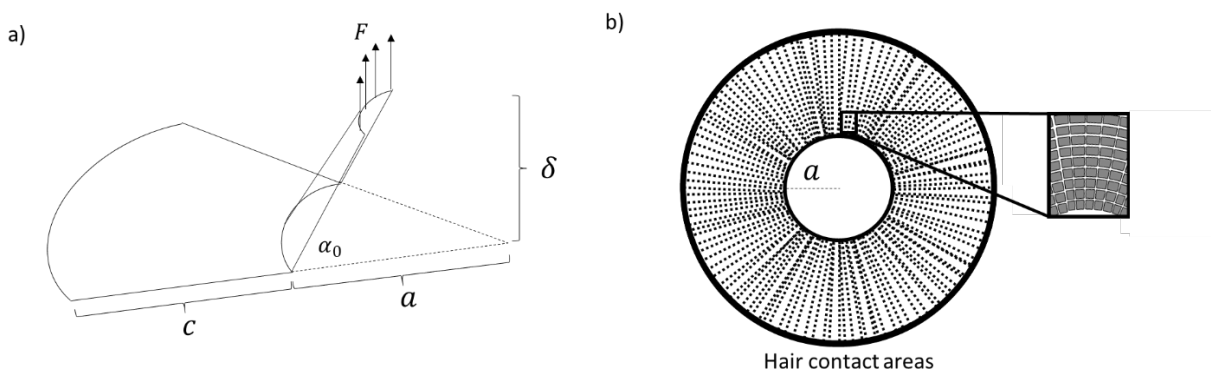

Figure 2: a) Schematic of the peeling of an elastic tape equipped with hairs; b) schematic of a single second -level tape (hair).

268

269 *Figure 3: a) Schematic of hierarchical levels up to the second order. b) Normalized peeling force vs. peeling*
270 *angle (Eq. (7)) for different ϵ parameter values and $\hat{\gamma}=4\cdot10^{-4}$.*
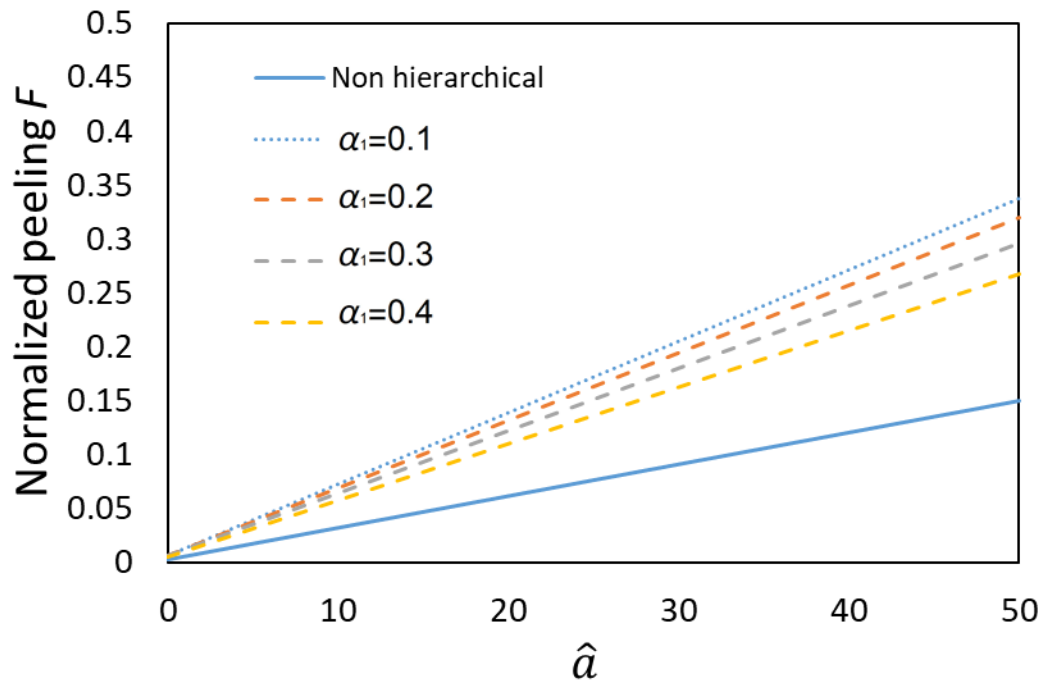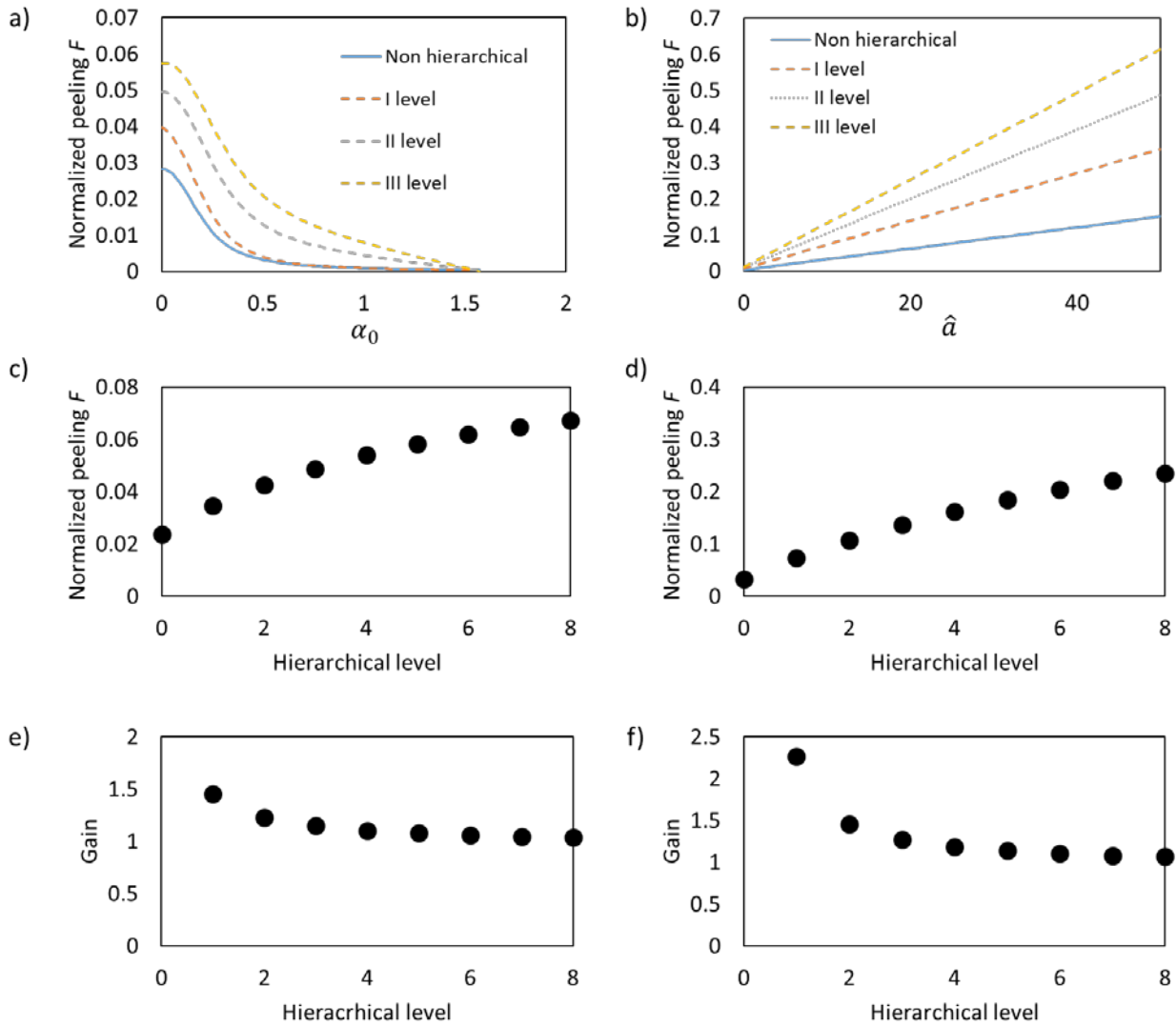
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272

273

274 *Figure 4: a) Schematic of the peeling of an axisymmetric membrane and b) schematic the contact region*
275 *between the hairs of the axisymmetric membrane and the substrate.*

276

277

278

279 *Figure 5: Peeling force for an axisymmetric membrane vs. detached radius $\hat{a}$ (Eq. (9)) for different α_1 values*
280 *($\hat{\gamma} = 4 \cdot 10^{-4}$).*

Figure 6: a) Normalized peeling force vs. peeling angle for increasing hierarchical levels in the case of a simple tape (ε = 0.05); b) Normalized peeling force vs normalized detached radius for increasing hierarchical levels in the case of an axisymmetric membrane (ε = 0.05 and α_0 = 0.1). c) Normalized peeling force as a function of number of hierarchical levels in the case of a simple tape (ε = 0.05 and α_0 = 0.1). d) Normalized peeling force as a function of number of hierarchical levels in the case of an axisymmetric membrane (ε = 0.05, $\hat{a}$ =10). e) Plot of the gain (Eq. 12) versus the hierarchical level for the simple tape and f) the axisymmetric membrane.

References

[1] L. A. Fuiman, C. M. Young, A. J. Gooday, and S. E. Shumway, *Advances in Marine Biology*. London, 2014.

[2] J. B. W. Roland C. Anderson, Jennifer A. Mather, *Octopus The Ocean's Intelligente Invertebrate*. Portland, 2010.

[3] A. M. Smith, "Cephalopod sucker design and the physical limits to negative pressure," *J. Exp. Biol.*, vol. 199, no. Pt 4, pp. 949–58, 1996.

[4] J. A. Sandoval, S. Jadhav, H. Quan, D. D. Deheyn, and M. T. Tolley, "Reversible adhesion to rough surfaces both in and out of water, inspired by the clingfish suction disc," *Bioinspir.*

298   *Biomim.*, vol. 14, no. 6, 2019.

299 [5]   F. Tramacere, M. Follador, N. M. Pugno, and B. Mazzolai, "Octopus-like suction cups: From
300   natural to artificial solutions," *Bioinspiration and Biomimetics*, vol. 10, no. 3, pp. 1–8, 2015.

301 [6]   M. Follador *et al.*, "Octopus-inspired innovative suction cups," *Lect. Notes Comput. Sci.*
302   *(including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics)*, vol. 8064 LNAI, pp.
303   368–370, 2013.

304 [7]   S. Baik, D. W. Kim, Y. Park, T. J. Lee, S. Ho Bhang, and C. Pang, "A wet-tolerant adhesive
305   patch inspired by protuberances in suction cups of octopi," *Nature*, vol. 546, no. 7658, pp.
306   396–400, 2017.

307 [8]   S. Sareh *et al.*, "Anchoring like octopus: biologically inspired soft artificial sucker," *J. R. Soc.*
308   *Interface*, vol. 14, no. 135, p. 20170395, 2017.

309 [9]   F. Tramacere, L. Beccai, M. J. Kuba, and B. Mazzolai, "Octopus Suckers Identification Code
310   (OSIC)," *Mar. Freshw. Behav. Physiol.*, vol. 46, no. 6, pp. 447–453, 2013.

311 [10]   F. Tramacere, L. Beccai, M. Kuba, A. Gozzi, A. Bifone, and B. Mazzolai, "The Morphology and
312   Adhesion Mechanism of Octopus vulgaris Suckers," *PLoS One*, vol. 8, no. 6, 2013.

313 [11]   F. Tramacere, A. Kovalev, T. Kleinteich, S. N. Gorb, and B. Mazzolai, "Structure and
314   mechanical properties of Octopus vulgaris suckers," *J. R. Soc. Interface*, vol. 11, no. 91, pp.
315   20130816–20130816, 2014.

316 [12]   W. M. Kier, "The Structure and Adhesive Mechanism of Octopus Suckers," *Integr. Comp.*
317   *Biol.*, vol. 42, no. 6, pp. 1146–1153, 2002.

318 [13]   F. Tramacere, N. M. Pugno, M. J. Kuba, B. Mazzolai, F. Tramacere, and B. Mazzolai,
319   "Unveiling the morphology of the acetabulum in octopus suckers and its role in
320   attachment," *J. R. Soc. Interface*, vol. 5, pp. 1–5, 2015.

321 [14]   A. J. Kinloch, *Adhesion and Adhesives*. Heildeberg, 1987.

322 [15]   K. Kendall, "Thin-Film Peeling - The Elastic Term," *J. Phys. D. Appl. Phys.*, vol. 8, pp. 1449–
323   1452, 1975.

324 [16]   M. Varenberg, N. M. Pugno, and S. N. Gorb, "Spatulate structures in biological fibrillar
325   adhesion," *Soft Matter*, vol. 6, no. 14, p. 3269, 2010.

326 [17]   N. M. Pugno, "The theory of multiple peeling," *Int. J. Fract.*, vol. 171, no. 2, pp. 185–193,
327   2011.

328 [18]   J. O. Wolff, I. Grawe, M. Wirth, A. Karstedt, and S. N. Gorb, "Spider's super-glue: Thread
329   anchors are composite adhesives with synergistic hierarchical organization," *Soft Matter*,
330   2015.

331 [19]   J. O. Wolff and M. E. Herberstein, "Three-dimensional printing spiders: Back-and-forth glue
332   application yields silk anchorages with high pull-off resistance under varying loading
333   situations," *J. R. Soc. Interface*, 2017.

334 [20]   L. Brely, F. Bosia, and N. M. Pugno, "Numerical implementation of multiple peeling theory
335   and its application to spider web anchorages.," *Interface Focus*, vol. 5, no. 1, p. 20140051,
336   2015.

[21]   Z. L. Peng, S. H. Chen, and A. K. Soh, "Peeling behavior of a bio-inspired nano-film on a substrate," *Int. J. Solids Struct.*, vol. 47, no. 14–15, pp. 1952–1960, 2010.

[22]   L. Brely, F. Bosia, and N. M. Pugno, "The influence of substrate roughness, patterning, curvature, and compliance in peeling problems," *Bioinspir. Biomim.*, vol. 13, no. 2, p. 026004, 2018.

[23]   Z. Peng and S. Chen, "Effect of bending stiffness on the peeling behavior of an elastic thin film on a rigid substrate," *Phys. Rev. E*, vol. 042401, pp. 1–7, 2015.

[24]   H. Gao, X. Wang, H. Yao, S. Gorb, and E. Arzt, "Mechanics of hierarchical adhesion structures of geckos," *Mech. Mater.*, vol. 37, no. 2-3 SPEC. ISS., pp. 275–285, 2005.

[25]   L. Brely, F. Bosia, and N. M. Pugno, "Emergence of the interplay between hierarchy and contact splitting in biological adhesion highlighted through a hierarchical shear lag model," *Soft Matter*, vol. 14, pp. 5509–5518, 2018.

[26]   Z. Peng and S. Chen, "Effect of pre-tension on the peeling behavior of a bio-inspired nano-film and a hierarchical adhesive structure," *Appl. Phys. Lett.*, vol. 163702, no. September, 2012.

[27]   F. Tramacere, E. Appel, B. Mazzolai, and S. N. Gorb, "Hairy suckers: The surface microstructure and its possible functional significance in the octopus vulgaris sucker," *Beilstein J. Nanotechnol.*, vol. 5, no. 1, pp. 561–565, 2014.

[28]   H. Yao and H. Gao, "Reprint of 'Multi-scale cohesive laws in hierarchical materials' [In. J. Solids Struct. 44 (2007) 8177-8193]," *Int. J. Solids Struct.*, vol. 45, no. 13, pp. 3627–3643, 2008.

[29]   B. Chen, P. . Wu, and H. Gao, "Hierarchical modelling of attachment and detachment mechanisms of gecko toe adhesion," *Proc. R. Soc. A Math. Phys. Eng. Sci.*, vol. 464, no. 2094, pp. 1639–1652, 2008.

[30]   L. Afferrante, G. Carbone, G. Demelio, and N. Pugno, "Adhesion of elastic thin films: Double peeling of tapes versus axisymmetric peeling of membranes," *Tribol. Lett.*, vol. 52, no. 3, pp. 439–447, 2013.

[31]   E. Arzt, S. Gorb, and R. Spolenak, "From micro to nano contacts in biological attachment devices," *Proc. Natl. Acad. Sci. U. S. A.*, 2003.

[32]   S. Baik, J. Kim, H. J. Lee, T. H. Lee, and C. Pang, "Highly Adaptable and Biocompatible Octopus-Like Adhesive Patches with Meniscus-Controlled Unfoldable 3D Microtips for Underwater Surface and Hairy Skin," *Adv. Sci.*, 2018.

[33]   Y. Wang *et al.*, "A biorobotic adhesive disc for underwater hitchhiking inspired by the remora suckerfish," *Sci. Robot.*, 2017.