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Design of a Biomimetic Skin for an Octopus-Inspired Robot – Part I: Characterising Octopus Skin

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Abstract

Octopus skin samples were tested under quasi-static and scissor cutting conditions to measure the in-plane material properties and fracture toughness. Samples from all eight arms of one octopus were tested statically to investigate how properties vary from arm to arm. Another nine octopus skins were measured to study the influence of body mass on skin properties. Influence of specimen location on skin mechanical properties was also studied. Material properties of skin, i.e. the Young's modulus, ultimate stress, failure strain and fracture toughness have been plotted against the position of skin along the length of arm or body. Statistical studies were carried out to help analyzing experimental data obtained. Results of this work will be used as guidelines for the design and development of artificial skins for an octopus-inspired robot.

Keywords: octopus skin, uniaxial tension, scissor cutting, Young's modulus, failure strain, fracture toughness

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1 Introduction

Scientists from robotics, biology and materials science have started to work together on an integrated project called OCTOPUS to investigate and understand the principles that give rise to the octopus sensory-motor capabilities and to incorporate them in new design approaches and technologies for building physically embodied, soft-bodied, hyper-redundant, dexterous artefacts[1]. Octopuses are considered to be the most intelligent invertebrate animal on the planet. As these animals are composed of muscular hydrostats and, thus, lacking a rigid skeleton[2], octopus arms have high flexibility and an infinite numbers of degrees of freedom. This extraordinary morphology, involving changeable stiffness, high dexterity complied with distributed controlling system has attracted enormous interests from scientists[2–9] and provides a source of inspiration for robotics[10,11]. A robot is planned that could locomote in water over a variety of terrains, explore narrow spaces, grasp objects and manipulate them effectively[12,13].

A key challenge in the development of soft-bodied robots is the development of functional skins. Skins of animals provide protective barrier for internal tissues and bones from the surrounding environments[14,15]. Apart from being waterproof, the skin frequently needs to have a high degree of mechanical functionality, for example containing internal tissues, deformation to accommodate shape changes in underlying muscular systems and protection against the mechanical challenges (contact with substrates, actions of predators) imposed by external environment. Similarly, skins for soft body robots like octopus are needed to contain and protect the artificial muscular units and control components, *etc*. Like real skins, the skin artefact should have mechanical properties designed so as not to impair the performance of the actuation systems.

Real octopus skin provides a very good sequence of standard design criteria for the development of the skin artefact for robot octopus. Measuring mechanical properties of real octopus skin is vital in the development of the skin artefact. This paper presents testing results of octopus skin under static loading conditions.

Measurement of soft tissue properties have been conducted by a number of researchers[16–19]. The indentation method used by researchers assumes that the

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thickness of the testing samples is semi-infinite[20–23] and is not able to identify the properties at different directions. In fact, most of the biological materials are anisotropic. Suction measurement used by Hendriks *et al*.[24], Cook *et al*.[25], and Khatyr *et al*.[26] and biaxial tests used by Lua *et al*.[27], Waldman and Lee[28], Lanir and Fung[29], and Lee *et al*.[30] are very useful methods to study planar deformation of soft tissues. To obtain constitutive behaviour of materials, uniaxial tests are necessary for anisotropic soft tissues and this method has been used widely[31–36].

Fracture toughness, defined here as the specific work of fracture, is one of the most important properties of biological materials[37]. For octopus skin, a minimum level of fracture toughness is vital when the octopus arms are wrapping around sharp objects, when the body makes contact with substrates, and when octopus is attacked by other animals with sharp teeth. The skin artefact for an octopus robot should have similar or higher fracture toughness compared with the real skin.

Cutting with instrumented scissors is a useful way to determine fracture toughness for biological tissues[38–45]. The work of fracture or fracture toughness can be calculated in a straightforward integration of force over displacement[38,41].

In this work, uniaxial tensile and scissor cutting tests were conducted to investigate the in-plane material properties and fracture toughness of octopus skin. Results obtained in this study will provide useful information and criteria for the design of the skin artefact for robotic octopus.

2 Materials and testing methods

2.1 Materials

Material tested in this study is octopus skins of both body and arm. Ten lesser octopuses (*Eledone cirrhosa* Lamarck) were purchased from a fishmonger and stored in a freezer. Foutz *et al*.[46] concluded that freezing does not affect the elastic and viscous properties of skin tissue. Skins were removed from the bodies or arms just before test and connective tissue was removed from the inner side of the skins. The skin samples were kept in iced water whenever possible during the preparation process. The thickness of the skin was measured by using a height gauge. The samples were first placed on a flat glass panel and the thicknesses were taken when the sample was slightly compressed by the gauge. The accuracy of the gauge is ± 0.01 mm. The width of the sample was measured at the same time. The range of sample thickness was typically between 0.8 mm and 0.15 mm.

To study the variant of material properties of skin of the eight arms of an octopus, arm skins from one octopus have been tested only in the longitudinal direction. Table 1 shows the results of tensile tests on arm skins of an octopus, mass 990 g. Arm numbering started from one and five from the symmetrical line on the ventral side and counted towards the posterior and stopped at the symmetrical line on the top side. So arms numbered one to four belonged to the left side of an octopus and those numbered five to eight belonged to the right side.

Table 1 Tensile testing results of arm skins of a 990 grams octopus, together with standard deviation

Arm	Max. E (MPa)	Failure strain (%)	Ultimate stress (MPa)
1	20.3 ± 3.5	39.0 ± 6.6	4.5 ± 1.6
2	22.4 ± 5.2	36.6 ± 5.4	5.2 ± 1.7
3	20.1 ± 6.8	37.0 ± 5.4	4.4 ± 1.5
4	23.1 ± 8.8	35.3 ± 6.2	5.0 ± 2.7
5	21.2 ± 5.6	38.5 ± 5.9	5.1 ± 1.9
6	20.5 ± 6.0	39.9 ± 5.9	4.0 ± 1.6
7	21.1 ± 6.4	36.1 ± 4.4	4.7 ± 1.4
8	21.6 ± 6.1	38.8 ± 5.5	4.9 ± 1.4
$F_{7,87}$	0.40	1.05	0.638
p-value	0.897	0.406	0.723

The locations of the skin specimens in the longitudinal and circumferential directions of the arms and body were also recorded to study regional variations in properties. The longitudinal locations of the arm skin were taken as the distance to the proximal arm. That of the body skin was the distance from the mantle side closer to the head.

In the circumferential direction, there are three stripes of arm skin, as shown in Fig. 1. The one opposite to the suckers is defined as Stripe 1, which is darker in colour. There are two side stripes on each of the suckers. They are numbered as Stripes 2 and 3. The body skin is considered to have two sides along the circumferential direction. One side is the dorsal skin which is facing up and the other side the ventral skin which is face down. The dorsal skin of the octopus is dark brown, while the skin on the ventral side is almost white.

Biomaterials are composite materials which have anisotropic properties. In this study, skins from octopus arm and body were tested in two directions. One direc-