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Characterizing the viscoelastic properties of the Sepia *Officinalis* lateral fins

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Characterizing the viscoelastic properties of the *Sepia officinalis* lateral fins

A bio-inspired approach to producing viscoelastic materials

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Preface

My name is Daan van den Bor, I am a fourth-year Applied Biology (BSc.) student at Aeres University of Applied Sciences Almere. For my final thesis, I chose to focus on biomimetics specifically focused on the cuttlefish. The research for this project is done at the Experimental Zoology group (EZO) of Wageningen University & Research (WUR) supervised by Dr. Brett Klaassen van Oorschot, Dr. Guillermo Amador, and Henk Schipper from the biomimetics lab.

I would like to thank Dr. Brett Klaassen van Oorschot, Dr. Guillermo Amador, and Henk Schipper from EZO, for their help and guidance throughout my thesis. Furthermore, I would like to thank Dr. Vittorio Saggiomo from the BioNanoTechnology Group (BNT) at WUR for his expertise in artificial materials. Lastly, I want to thank Tom Huisman from Aeres University of Applied Sciences Almere for his feedback and help on the project.

I changed the introduction because I included the reason to choose the cuttlefish as a model organism, I explained what the advantages of undulatory thrust underwater are compared to propeller thrust, and I excluded the focus on the contribution of the separate tissues in the sub-questions and hypothesis due to time constraints. Instead, I added a sub-question looking into the influence of water and salinity on the material. Additionally, I made changes in the materials & methods with a broader description, and I changed the model I used from the quasilinear model to the Peleg model since that was eventually the better option.

August, 2023

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Abstract

The European common cuttlefish (Sepia *officinalis*) makes use of undulatory locomotion through its lateral fins. This type of locomotion shows good potential for application for underwater vehicle thrust because it gives the user advantages like maneuverability, stable station keeping, and energy efficiency. This type of locomotion in the cuttlefish is partly made possible because of the viscoelasticity of the fins. By mimicking the viscoelasticity of the cuttlefish fins into an artificial material the benefits of undulatory movement can be used in robotic application, within the field of soft robotics. In this project a material that possibly can be used for this type of application is found by mimicking the viscoelasticity of the cuttlefish fins. To find this material the viscoelastic properties of the cuttlefish fins have been measured and compared with artificial materials showing the same type of viscoelastic behavior. The material has also been tested on the influence of an aqueous environment to accurately mimic the viscoelasticity and to test its potential for underwater usage. Viscoelasticity of the selected artificial material as well as the cuttlefish fins have been tested through impact indentation. The indentation results were computed with the Peleg model so the model values could be statistically compared across the natural and artificial material. The results show that the cuttlefish fins have a relatively fast relaxation time, and the solidity of the material is close to a liquid. Ecoflex 00-10 has been selected to be tested and compared with the cuttlefish. This material shows good customizability of its viscoelastic properties that can be adjusted to fit the properties of the cuttlefish. The Ecoflex has a very similar relaxation time, however the Ecoflex is slightly more solid compared to the cuttlefish. The exposure to water and salinity does influence the viscoelastic behavior of the Ecoflex making the viscoelastic properties exceed the properties of the cuttlefish. However, the Ecoflex has been created with different ratios and the ratio 1:3 shows no significant difference to the cuttlefish even when exposed to water and salinity. So, it can be concluded that Ecoflex 00-10 with a chemical composition ratio of 1:3 shows very similar viscoelasticity to the cuttlefish's lateral fins. Recommendations for the future include investigating the viscoelasticity of the cuttlefish with other models and adjusting the chemical composition of the Ecoflex 00-10 further to fit the viscoelasticity of the cuttlefish to the fullest extent.

Samenvatting

De Europese gewone zeekat (Sepia officinalis) maakt gebruik van golvende voortbeweging door middel van zijn zijvinnen. Deze manier van voortbewegen biedt goede toepassingsmogelijkheden voor de stuwkracht van onderwatervoertuigen, omdat het de gebruiker voordelen biedt zoals wendbaarheid, stabiel stationair houden van het voertuig en energie-efficiëntie. Dit type voortbeweging bij de zeekat is deels mogelijk door de visco-elasticiteit van de vinnen. Door de visco-elasticiteit van de vinnen van de zeekat na te bootsen in een kunstmatig materiaal kunnen de voordelen van de golvende beweging worden gebruikt in robottoepassingen op het gebied van soft robotics. In dit project wordt een materiaal gevonden dat mogelijk gebruikt kan worden voor dit soort toepassingen door de visco-elasticiteit van zeekatvinnen na te bootsen. Om dit materiaal te vinden zijn de visco-elastische eigenschappen van de vinnen van zeekatten gemeten en vergeleken met kunstmatige materialen die hetzelfde soort visco-elastische gedrag vertonen. Het materiaal is ook getest onder invloed van water om de visco-elasticiteit nauwkeurig na te bootsen en het potentieel voor gebruik onderwater te testen. De visco-elasticiteit van het geselecteerde kunstmatige materiaal en de zeekatvinnen zijn getest door middel van impactindentatie. De indentatieresultaten werden berekend met het Peleg model zodat de modelwaarden statistisch vergeleken konden worden tussen het natuurlijke en kunstmatige materiaal. De resultaten laten zien dat de vinnen van de zeekat een relatief snelle relaxatietijd hebben en dat de soliditeit van het materiaal dicht bij een vloeistof ligt. Ecoflex 00-10 is geselecteerd om getest en vergeleken te worden met de zeekat. Dit materiaal toont een goede aanpasbaarheid van de visco-elastische eigenschappen die kunnen worden aangepast aan de eigenschappen van de zeekat. De Ecoflex heeft een vergelijkbare relaxatietijd, maar de Ecoflex is iets steviger in vergelijking met de zeekat. De blootstelling aan water en zoutgehalte beïnvloedt het visco-elastische gedrag van de Ecoflex, waardoor de visco-elastische eigenschappen groter worden dan die van de zeekat. Ecoflex is echter gemaakt met verschillende verhoudingen en de verhouding 1:3 vertoont geen significant verschil met de zeekat, zelfs niet bij blootstelling aan zout water. Er kan dus geconcludeerd worden dat Ecoflex 00-10 met een chemische samenstellingsverhouding van 1:3 een visco-elasticiteit heeft die vergelijkbaar is met die van de laterale vinnen van de zeekat. Aanbevelingen voor de toekomst zijn onder andere het onderzoeken van de visco-elasticiteit van de zeekat met andere modellen en het verder aanpassen van de chemische samenstelling van Ecoflex 00-10 om de visco-elasticiteit van de zeekat zo goed mogelijk te benaderen.

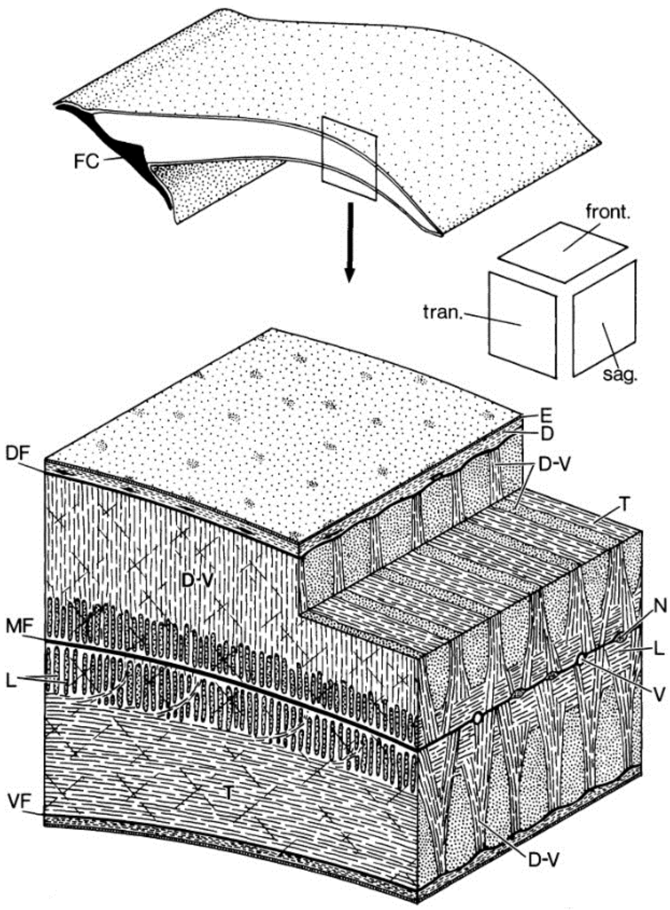
1. Introduction

Humans have been using nature as a source of inspiration for over 3000 years. Biological phenomena are used as inspiration in fields like engineering, design, chemistry, robotics and much more. The study of essentially mimicking natural phenomena has only relatively recently been named biomimetics. (Vincent et al., 2006) Recently, this study has been applied more in robotics. For example, Sfakiotakis et al. (2015a) have been looking into using undulatory fin movement seen in different aquatic organisms as an inspiration for the artificial propulsion of underwater vehicles (UVs). Undulatory locomotion underwater gives a UV low-speed maneuverability and stable station-keeping capabilities because of the thrust vectoring capacity. Other advantages compared to propellor propulsion include high energy efficiency, reduced sediment disruption, and stealth movement. (Unmanned) UVs with these abilities can be used in scientific studies, preservation and sustainable exploitation of marine offshore resources, inspection/maintenance tasks, and operation in nearshore environments (Sfakiotakis et al., 2016). One natural undulatory fin movement expert that has not been mimicked accurately is the European common cuttlefish (*Sepia officinalis*) which uses its lateral fins to create this undulatory movement, giving it the ability to hover in the water and make low-speed movements (Kier & Thompson, 2003). By looking at the biomechanical behavior of the fins, much can be learned about creating such movements and mimicking them artificially for UV propulsion.

To understand the biomechanics of the fins, the fin anatomy should be studied first. Actuation of the fin happens through the muscular hydrostat that makes up the musculature across the fin. The musculature is built up out of different muscle layers, positioned in three mutually perpendicular orientations. During slow fin beating, EMG activity analysis suggests that muscles in the dorsal part of the fin cause upward movement of the fin. This movement is supported by the crossed oblique connective tissue since no EMG activity is found in the ventral part of the fin during upward movement. Correspondingly, during the downward fin beating the muscles of the ventral part of the fin are active and supported by the connective tissue instead of the dorsal muscles. When fin beating is increased, muscles of all orientations work together because more support is needed due to an increase in force and amplitude. In figure 1 the different tissues found in the cuttlefish fin are displayed. These include all the different muscle orientations, skin, cartilage, and connective tissue. This multilayered structure of different tissue types should be mimicked to create a robotic fin based on the biomechanics of the fin. (Kier, 1989) (Kier et al., 1989)

Figure 1

Fin musculature of cuttlefish and squid



Schematic diagram of the microanatomy of the fin of Sepia oficinalis. The sectional planes (front., frontal: tram, transverse; sag., sagittal) are indicated. D, dermis; DF, dorsal fascia; D-V, dorso-ventral muscle; E, epidermis: FC, fin cartilage; L, longitudinal muscle; MF, median fascia: N, fin nerve; T, transverse muscle: V, blood vessel; VF, ventral fascia. Acquired from ''The fin musculature of cuttlefish and squid (Mollusca, Cephalopoda): morphology and mechanics'' by W. M. Kier, 1989, *Journal of Zoology, 217,* p.27. In public domain.

The concept of undulatory locomotion based on fin movement has been studied before. For example, Sfakiotakis et al. (2015b) have looked at multiple aquatic species utilizing undulatory fin movement for creating a bio-inspired fin. This resulted in a working fin with the desired efficacy when attached to a robot (Sfakiotakis et al., 2016) however, this robot uses rigid rays in the fin to form structure and resistance. Cuttlefish lack such rigid counterparts but instead rely on their muscular hydrostat for structure and resistance (Kier, 1989). Arslan and Akça (2019) have built an amphibious vehicle inspired by cuttlefish fins. However, they implemented rigid rays in their design as well, not accurately mimicking the biomechanics of the cuttlefish fins. Additionally, the individual fin rays must all be actuated which reduces its power and material efficiency. By focusing more on the behavior of the fin material, robots are expected to need much less actuation. The material should create the undulatory movement by itself by giving the material the right viscoelasticity. That will give the fin undulatory movement without needing as much actuation. This makes the cuttlefish a much better model organism compared to other aquatic species like rayfish. This approach utilizes the field of soft robotics.

Soft robotics makes use of material science to mimic complex natural structures like cuttlefish fins. This approach is more aligned with an accurate portrayal of the cuttlefish fin biomechanics. Potential benefits of this method could be, power efficiency, cost efficiency, material efficiency, simplicity, light-weightiness, and maybe even efficacy. (Whitesides, 2018) Since the type of material is very important, the mechanical properties of the cuttlefish fins should be measured to be able to pick an accurate material.

In this study, the viscoelastic properties of the cuttlefish fins will be measured and applied to artificial materials. Viscoelasticity is the most relevant material property to mimic to get a similar fin movement (Coyle et al., 2018). This can be measured via a stress-relaxation test. After measuring the viscoelastic properties of the cuttlefish, the properties can be recreated inside an artificial material. The main research question of this study is: 'What artificial material(s) has/have the same viscoelastic properties as the European common cuttlefish's (*Sepia officinalis*) lateral fins?'. To help answer this question, some sub-questions are drawn up:

1. What are the viscoelastic properties of cuttlefish fins?
2. What artificial material shows potential similar viscoelastic behavior as the cuttlefish fins?
3. What is the difference in viscoelasticity of the selected artificial material in air, water, and saline water?

Not only will this help in mimicking the undulatory movement for artificial use, but it will also help better understand the fin's physiology.

There are close to no studies on the viscoelastic properties of the cuttlefish, or any other cephalopod. Based on the cuttlefish's anatomy it is expected that the viscosity and elasticity overall will be relatively high due to the soft tissues. (Kier, 1989) A material that will likely show similar material behavior to the cuttlefish fin is Ecoflex 00-10. This material is described as having tissue mimicking properties, durability, and reasonable stability over time (Yasar et al., 2012). The material is also very customizable in terms of its material properties so it seems this would be a good option.

Reader's guide

In the first chapter, the introduction is described. In the second chapter, the materials and methods are explained. In chapter 3 the results are displayed. In chapter 4 the discussion is shown. In chapter 5 the conclusion and recommendations are drawn up. Then the used literature is listed. And lastly, the appendices are put in.

2. Materials & Methods

To figure out what artificial material has similar viscoelastic properties as the cuttlefish fins, the viscoelasticity of the fins must be measured first. This is done by measuring the fin's relaxation time with impact indentation. The results of this experiment were computed with a viscoelastic model to interpret the viscoelasticity. After determining the viscoelasticity of the cuttlefish an appropriate artificial material could be selected and measured. Lastly, the selected material was tested on the influence of water and saline water on its viscoelasticity. All data has been tested on statistical significance with a statistical test. The methodology for this project is inspired by similar research done by Mijailovic et al. (2018).

2.1 Measuring viscoelasticity of the cuttlefish's lateral fins

To be able to measure the viscoelasticity of cuttlefish fins you will have to first obtain the biological specimens themselves and prepare them correctly for the experiment. Then you can do the indentation measurement and compute the results to usable data through first applying a data processing filter and after use a viscoelastic model. By executing these steps an answer on the first sub-question (What are the viscoelastic properties of the cuttlefish fins?) was obtained.

2.1.1 Biological specimen

The cuttlefish used in this experiment have been obtained from a fresh fish delivery service. Transportation to Wageningen was done in a cooled vehicle so they could remain fresh. In total three cuttlefish have been used for this experiment varying in weight from 329 g to 555 g and in mantle length from 13 to 16 cm. Every cuttlefish has been measured on different days since the measurements took a day per cuttlefish and the cuttlefish had to be as fresh as possible. Immediately after delivery the specimens were washed and put into 3.5% saline water on ice (average salinity of world's oceans). The specimens were weighed, measured, and photographed. After which the fins were removed from the rest of the body. The fins were marked in a 1 by 2 cm grid pattern to determine the indentation points. The fin was photographed again with the grid pattern (figure 2). With the help of the measuring device that can be seen in figure 3 the fin thickness for every measurement point was measured so that could be used for the indentation settings. The thickness for every point on the grid pattern was measured.

Figure 2

Image of cuttlefish fin with drawn-on grid pattern

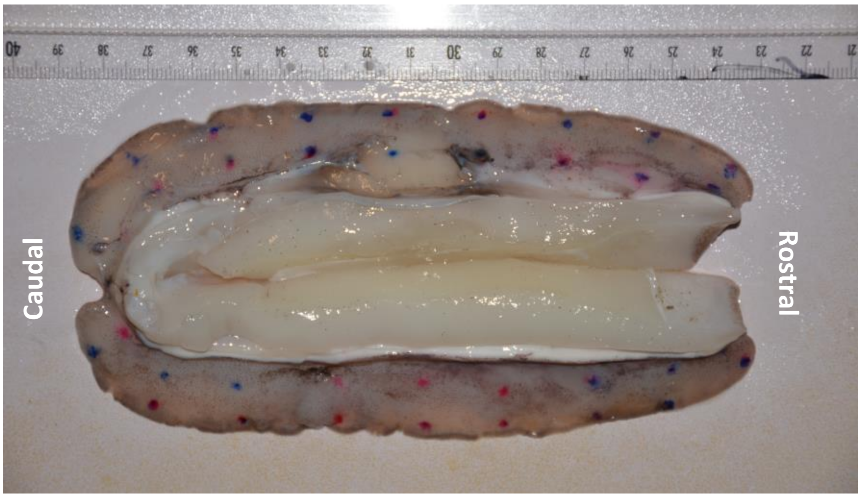


Figure 3

Schematic of tissue measuring device created on fusion 360

2.1.2 Indentation testing

Figure 2

Indenter setup with cuttlefish fin

The viscoelastic properties of the fin's tissue layers have been measured with a stress-relaxation test. A good technique for this is the use of impact indentation (Mijailovic et al., 2018). This works by applying a certain preset strain applied by a Futek (Irvine, CA, USA) 20-g force transducer. The setup can be seen in figure 4 This device is equipped with a strain gauge that will track the stress and a spherical indentation tip which is satisfactory for viscoelastic measurements (Cheng et al., 2005). In the case of a viscoelastic material, the stress will precede the strain. The addition of load will result in an increasing elongation response. (Vogel, 2013)

The indenter was controlled by the MATLAB script that can be found in Appendix I. The sampling frequency was set to 1000 Hz, the indentation speed at 1 mm/s, and the pre-set strain differed for every measurement point. As discussed in paragraph 2.1.1 the tissue thickness was measured for every indentation point. For every point, the strain was set to 10% of the tissue thickness at that point and immediately after another measurement was done at the same point at 30% of the tissue thickness. This was done to see if there is difference in viscoelasticity when more of the tissue is involved in the relaxation of the material. This process has been replicated for every measuring point on the fin and the different tissues.

The measurement of the fin was done outside of the water because the fin would not stick to the surface. But the sample was put back in the water on multiple occasions to prevent osmotic variation.

2.1.3 Data processing filter

Before computing the indentation data, a 5th order low pass Butterworth filter (Butterworth, 1930) was applied to all measurements. This filter smooths out the frequency response by filtering out noise and ripples. The frequency cutoff was set to 5 Hz. This filter is included in the script for the viscoelastic model computation in Appendix II.

2.1.4 Viscoelastic model

Similar research has been conducted looking at the viscoelastic properties of the Crucian carp (Carrasius *auratus*) fins, muscle, and skin by Ming et al. (2011). They used the fractional Zener or SLS model. This model describes the most used simple models namely the Maxwell model and the Kelvin-Voigt model. The Zener model combines these models into one to receive all relevant parameters for viscoelasticity. Nonetheless, in subsequent research, it was discovered that the Zener/SLS model is not able to reproduce the rheological behavior with optimal accuracy (Feng et al., 2017). In addition, this model is too detailed which makes it near to impossible for comparison between samples or in the case of this research, the real fin with the artificial fin (Thielen et al., 2013). Another simple model is the Peleg model (Peleg, 1980), application of this model results in two parameters that can be easily compared. Namely, k1, which is the initial decay rate of the relaxation process, and k2, which is a measure of the sample’s solidity. The first step of the model is to normalize and linearize the relaxation curves that are computed by the MATLAB script in Appendix I with the following equation:

$$Y(t) = \frac{F(0) - F(t)}{F(0)} \quad (1)$$

Y(t) is the decay parameter, F(0) is the initial value of the decay parameter F, and F(t) is the value of the decay parameter at time t. The equation describing the relationship between Y(t) and t in its linear form is:

$$\frac{t}{Y(t)} = k1 + k2 * t \quad (2)$$

As mentioned before k1 is the initial decay rate and k2 is the measure of the sample's solidity, and they are the constants representing the intercept and the slope of the linear regression line. The model is computed with the custom script that can be found in Appendix II. This model is also helpful for the visualization of viscoelasticity. All the points measured on the fin have been computed into the Peleg model parameters. With these parameters, the variation of the viscoelasticity of the fin could be displayed as can be seen in figure 8.

2.2 Viscoelasticity of artificial material

In this paragraph an eligible artificial material was selected by checking multiple material properties. Firstly, the Young's modulus of the cuttlefish fin tissue had to be determined to find a material with similar elasticity. Next to elasticity the material has been evaluated on other material properties to see if the material is applicable for robotic usage. After selection, the material has been tested to see if the viscoelastic properties are compatible with those of the cuttlefish. Following these steps have led to an answer on the second sub-question (What artificial material shows potential similar viscoelastic behavior as the cuttlefish fins?) of this report.

2.2.1 Selecting eligible artificial material

The artificial material has been selected based on its material properties. Most importantly the viscoelasticity must be very similar to the cuttlefish fin. However, this material property is not known for numerous materials. A variable that is often used to compare the flexibility of different materials is the Young's Modulus. The results of the cuttlefish indentation experiment were translated into a Young's Modulus with the following equation:

$$\frac{\frac{F_{peak}}{\pi * (C)^2}}{\varepsilon} \quad (3)$$

This equation merely gives an indication of the Young's Modulus of the cuttlefish fin tissue. F_{peak} is the peak force measured by the indenter. C is the cross-sectional area of the spherical indenter. And ε is the pre-set strain of the measurement. The outcomes of these results were compared with Young's moduli of eligible materials.

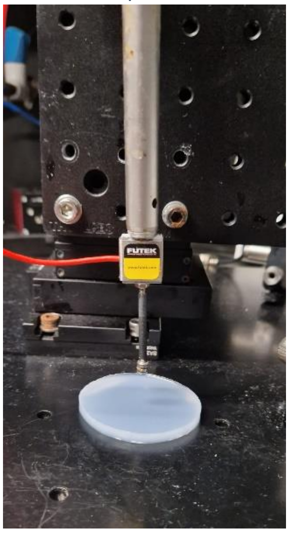
As is the goal of this study, the artificial material must have a similar viscoelasticity. But for the material to be applicable for actual robotic usage, it needs to meet some more requirements. Often a material's viscoelasticity has a trade-off with its strength, however for robotic usage the material still needs decent strength to prevent rupture. Additionally, the material needs to be resistant to breakdown in an aqueous environment with fluctuating salinity as the robot will be used underwater for long durations. The material should be able to withstand other fluctuating parameters like temperature and UV radiation. To pose no threat to the environment the material cannot be toxic and must be biocompatible to not interfere with the underwater environment. Lastly, production and maintenance should be relatively conventional to reduce cost.

2.2.2 Testing viscoelasticity of the artificial materials

After choosing the most eligible materials that was evaluated, the material had to be tested. The material has been created and put into Petri dishes. The ratio of the chemicals was altered to change its viscoelasticity and see which one is closest to the cuttlefish. The samples were created with ratios of 1:1, 1:2, and 1:3. Two chemicals had to be combined and vacuum sucked to remove air bubbles. The Petri dishes were sprayed with a mold releasing agent before, to be able to get the samples out. The samples were allowed to cure for at least 4 hours. In figure 5 an artificial material sample that is being tested is shown.

Figure 3

Indentation of artificial material sample



The material was tested in the same way as the biological samples. The indenter was used again, and the results were computed with the Peleg model. However, the artificial samples were tested only tested in the middle of the sample instead of all over as with the cuttlefish. The materials have been tested on all points twice, first at 10% indentation strain and after at 30% indentation strain.

2.3 Viscoelasticity of the artificial material in air, water, and saline water

In the last paragraph, the testing of the material in different conditions is described. Since an eventual robot will be used underwater, the material had to be tested when exposed to water and saline water. By doing these measurements an answer on the 3rd sub-question (What is the difference in viscoelasticity of the selected artificial material in air, water, and saline water?) could be obtained.

2.3.1 Preparation and testing viscoelasticity in water and saline water

The influence of water and saline water on the viscoelasticity of the selected artificial material has been determined. In addition to producing the artificial material samples described in paragraph 2, some more samples have been made. The other samples, also in the three different ratios, have been submerged in water and saline water. So, three sets of three ratios have been tested, one that is dry, one that has been put into water for at least 24 hours, and the other set has been submerged in 3.5% saline water for at least 24 hours as well.

The wet samples were tested exactly like the other samples and the cuttlefish fin. They were taken out of the water just before testing to replicate the methodology used for the cuttlefish. This way only the potentially absorbed water will be able to influence the outcome.

2.4 Statistical analysis

To detect significant differences between the biological samples and the artificial samples, Welch's analysis of variance (ANOVA) tests has been conducted. To compare the viscoelastic properties of the same material the repeated-measures analysis of variance (ANOVA) has been used. These tests were computed with RStudio software. The two parameters of the Peleg model, k1 and k2, have been used for comparison. Significance is reached at P = 0.05 or lower.

3. Results

In this chapter the experimental results are displayed. At first the results of the viscoelastic measurements of the cuttlefish fin are shown, the differences of viscoelasticity between specimens are compared, then the differences in viscoelasticity across the fins are visualized, and lastly the difference between a 10% and 30% indentation strain are compared. In the second paragraph, the most eligible artificial material has been selected and measured for viscoelasticity. The results of the viscoelasticity have been compared to the viscoelasticity of the cuttlefish fins after. And finally, in the third paragraph the artificial material has been tested on the influence of water and saline water on its viscoelasticity. These results were also compared with a statistical test. The raw data can be found in Appendix III.

3.1 Viscoelasticity of the cuttlefish fins

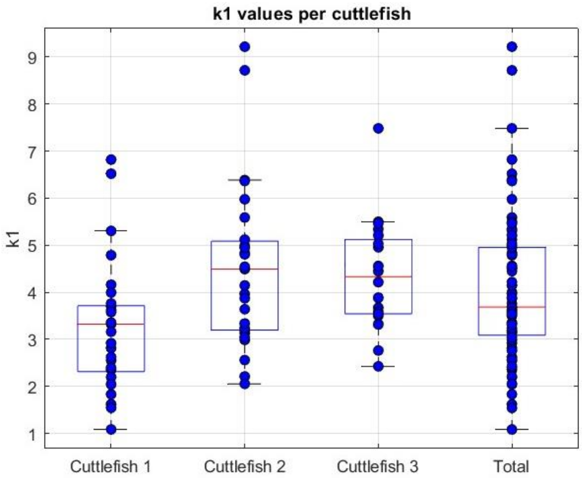
The viscoelasticity has been tested on three specimens. The Peleg results for every individual point measured can be found in Appendix III. The red rows indicate a faulty measurement, those are excluded from the results presented in this paragraph. The results are first compared by looking at the differences between the viscoelasticity of the separate specimens. Then the variation of viscoelasticity across the fins is presented. Lastly, the influence of 10% versus 30% indentation strain have been compared to see if the viscoelasticity changes due to the contribution of other tissues. This has answered the question: 'What are the viscoelastic properties of the cuttlefish fins?'.

3.1.1 Viscoelastic differences between the different cuttlefish

In figures 5 and 6, boxplots show the dispersion of the k1 and k2 values retrieved from the Peleg model per individual cuttlefish fin and the total of the three. Cuttlefish 1 shows relatively low values for k1 and k2. Cuttlefish 1 and 2 have very similar k1 and k2 values but show a substantial difference in the k2 values. Overall, the k1 values seem to mostly be between 3 and 5, the k2 values are all very close to 1 and vary mostly between 1.2 and 1.5. The distribution of the k1 values for every cuttlefish seems quite centered. The k2 value of cuttlefish 2 shows a fairly spread distribution with a notable number of outliers, the distribution of cuttlefish 3 looks very centered in comparison. For statistical analysis between the specimens, multiple variables have been taken into account: the weight of the cuttlefish, the length of the fin, and the used indentation strain. The placement of the measurements on the fin has been used as an error term. There is a significant difference found in both the k1 values ($p = 0.01$) and the k2 values ($p < 0.005$) between the cuttlefish.

Figure 4

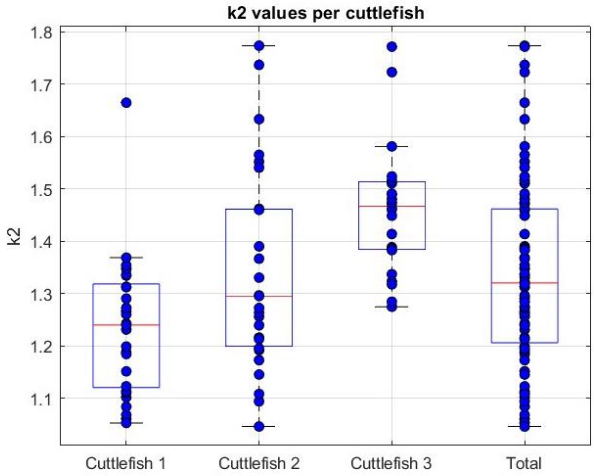
Boxplots showing the distribution of k1 values for every cuttlefish



* The blue dots represent the individual data points.

Figure 5

Boxplots showing the distribution of k2 values for every cuttlefish



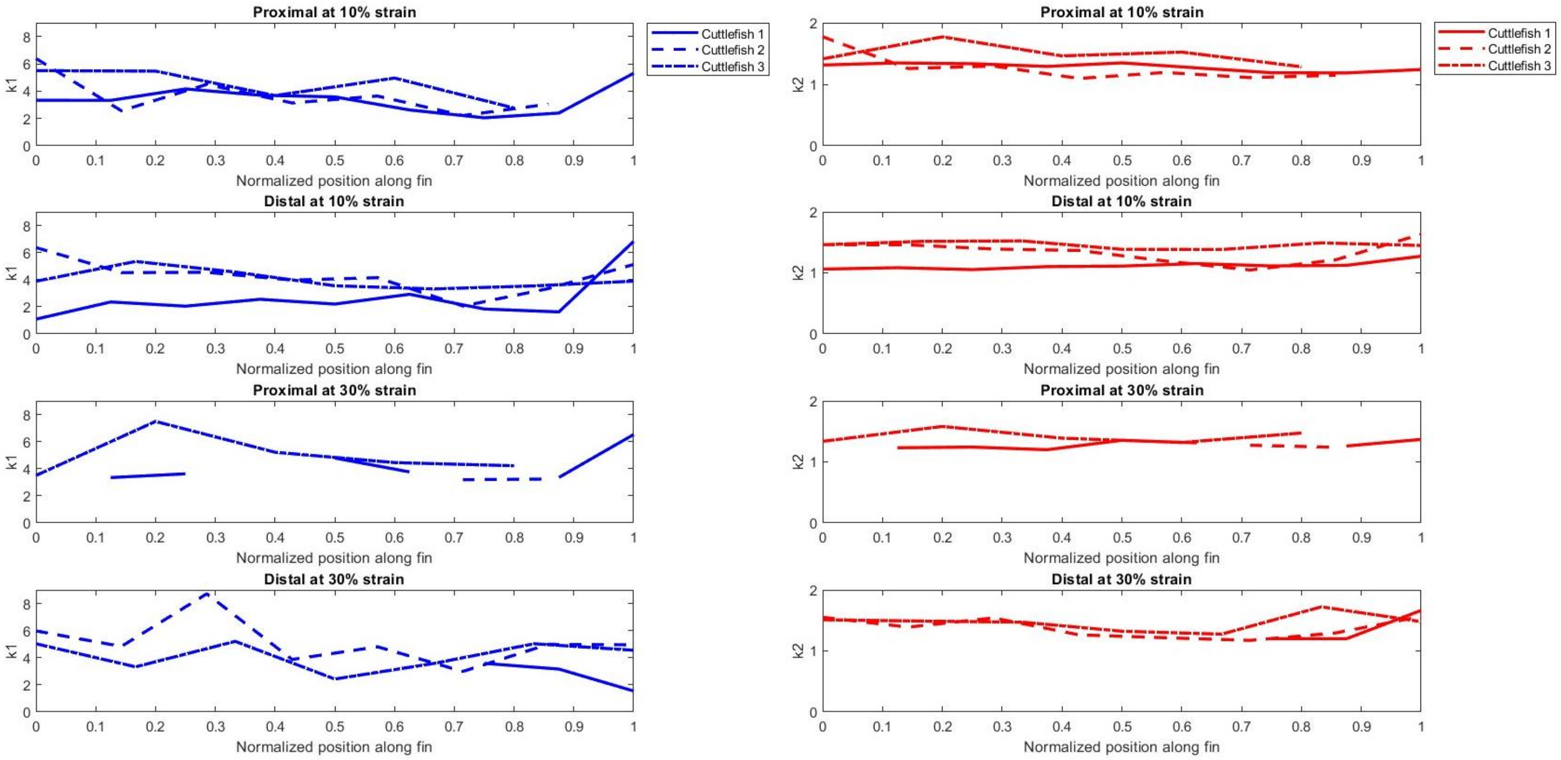
* The blue dots represent the individual data points.

3.1.2 Variation of viscoelasticity across the fin

In figure 7 all Peleg results for the three cuttlefish are displayed at their normalized position across the fin. The results have been separated by strain percentage (10%/30%), k value (k1/k2), and position on the fin (proximal/distal). At first look the values seem to be quite synchronized except for the k1 values of the proximal and distal positions at 30% strain. Not only is the variation of k1 values for the cuttlefish separately particularly spread but also the cuttlefish compared to each other are relatively spread. The k1 values at the proximal and distal position at 10% strain are more evenly distributed compared to each other and on their own. Notably cuttlefish one seems to have relatively lower k1 values at the caudal side of the fin at the distal position at 10% strain. At the proximal position, the rostral side of the fin seems to have relatively high k1 values. All k2 values are notably evenly distributed. Both on their own and compared to each other. Cuttlefish 3 seems to have slightly higher k2 values but still very comparable to the other cuttlefish. Statistical testing shows no significant difference ($p > 0.05$) in k1 and k2 across the areas within an individual.

Figure 6

k1 and k2 values variation across normalized fin



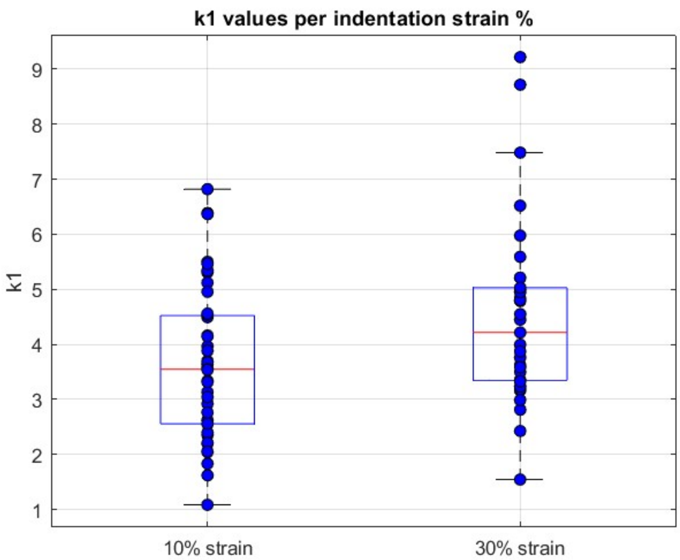
**Normalized position 0 is the rostral side of the fin and 1 is the caudal*

3.1.3 Viscoelastic differences between 10% and 30% strain

Figures 9 and 10 show the differences of k1 and k2 values for 10 and 30% indentation strain. At 30% indentation strain both k values seem to increase. For all values the distribution of data points are quite spread. However, the statistics show no significant difference ($p > 0.05$) between strain percentages for both k1 and k2.

Figure 9

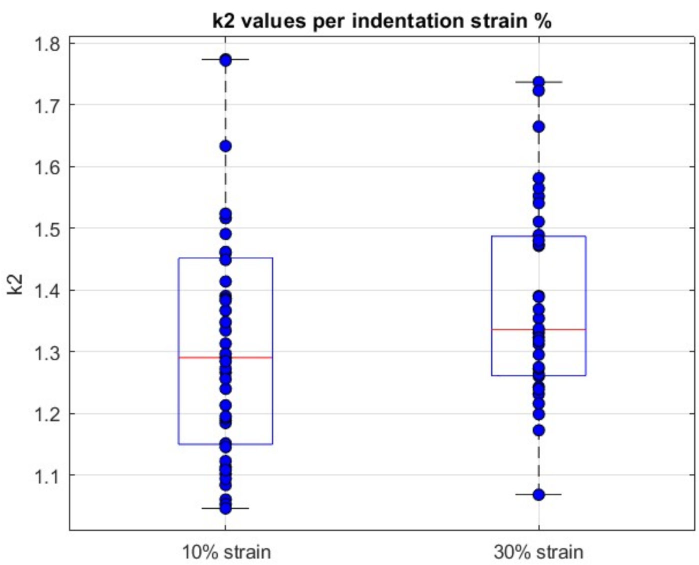
Boxplots showing the distribution of k1 values for 10% and 30% strain



* The blue dots represent the individual data points.

Figure 10

Boxplots showing the distribution of k2 values for 10% and 30% strain



* The blue dots represent the individual data points.

3.2 Viscoelasticity of artificial material

An artificial material has been selected to compare with the cuttlefish fin. The selected artificial material has been fabricated at different chemical ratios. The k values of the ratios have been compared to each other and after to the cuttlefish fin. This has answered the question: 'What artificial material shows potential similar viscoelastic behavior as the cuttlefish fins?'.

3.2.1 Selection of artificial material

When the viscoelastic properties of the cuttlefish fins were measured, the Young's moduli were computed with equation 3. Roughly the Young's moduli of the cuttlefish fins varied between 50 kPa and 200 kPa. When comparing this to some artificial elastomer Young's moduli the material Ecoflex 00-10 appeared to be low enough at 50 kPa (Vaicekauskaite et al., 2020). By altering the ingredient ratios, the viscoelasticity can be customized. Another viscoelastic artificial material is hydrogel. With the help of crosslinking, the Young's moduli of hydrogels can be altered from 1 kPa to 240 kPa (Xia et al., 2017), which is within the range of the cuttlefish tissue.

Ecoflex is a commercially available elastomer that is a popular choice in the field of soft robotics. It has various advantages for usage including non-toxicity, thermal stability, climate, oxidative, and ultraviolet resistance, high producibility, large deformability, and variability (Liao et al., 2020). Ecoflex is available in multiple shore hardness's including Ecoflex 00-10, Ecoflex 00-30, and Ecoflex 00-50. Based on preliminary study done by WUR (personal communication, 22 March 2023) on the viscoelasticity of Ecoflex 00-30 compared to the viscoelasticity of cuttlefish tissue including the fin, the material was too stiff and did not have enough viscosity. However, Ecoflex 00-10 is softer, which means that its viscoelasticity changes as well.

Hydrogels are very customizable and can be made from numerous materials. The material is described as having material properties similar to natural tissue and it mostly consists of water. The material's viscoelasticity, biocompatibility, biodegradability, mechanical strength can be altered with the help of crosslinking agents and other additives (Cheng et al., 2019). However, hydrogels appear to have limited stability and mechanical strength (Das et al., 2021), as was also discovered during preliminary testing.

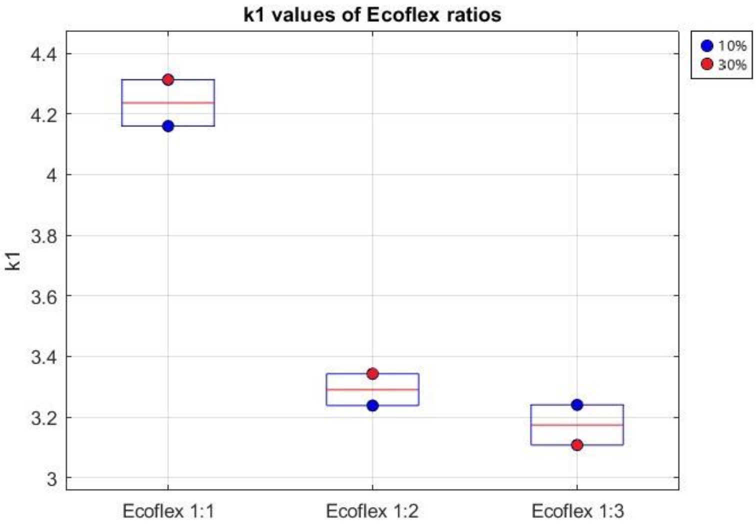
Due to the limitations of hydrogels in their mechanical strength and stability, Ecoflex 00-10 was found to be most eligible for viscoelastic testing and comparison with cuttlefish tissue. Different ratios of the material were created to see what formulations comes close to the cuttlefish tissue.

3.2.2 Viscoelasticity of Ecoflex 00-10 at different ratios

In figure 11 and 12 the k1 and k2 values of different ratios of Ecoflex 00-10 are shown. There seems to be close to no difference between 10% and 30% strain for all Ecoflex samples. There is a decrease in both k1 and k2 values for ratio 1:3. Both values of 1:2 and 1:3 show similar results compared to 1:1. Statistical analysis shows a significant difference ($p < 0.005$) between ratios of Ecoflex for both k1 and k2.

Figure 11

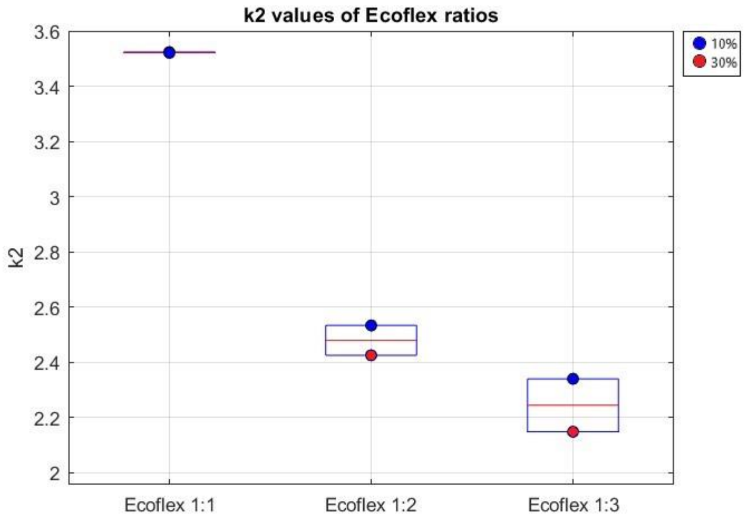
k1 values of different ratios of Ecoflex 00-10



* The dots represent the individual data points, blue = 10% strain and red = 30% strain

Figure 12

k2 values of different ratios of Ecoflex 00-10



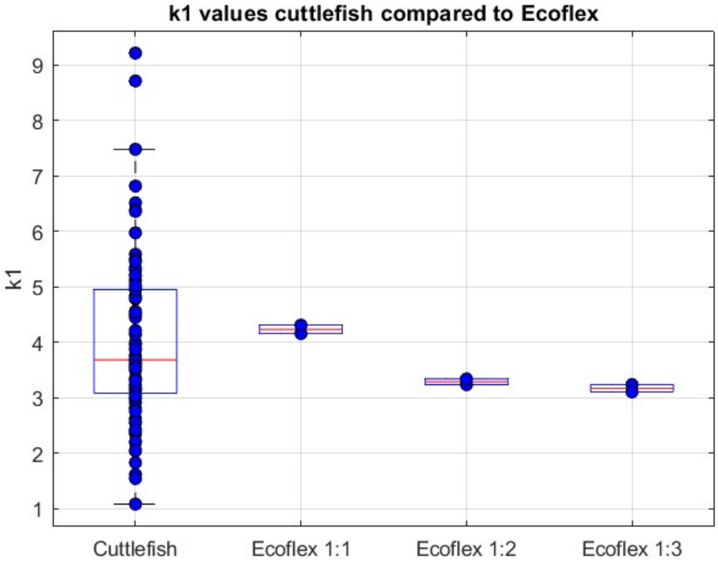
* The dots represent the individual data points, blue = 10% strain and red = 30% strain

3.2.3 Comparison between Ecoflex 00-10 and cuttlefish fin

Viscoelastic differences of Ecoflex 00-10 at different ratios and the cuttlefish fin can be observed in figure 13 and 14. The k1 values of the Ecoflex ratios are distinctly similar to the cuttlefish fin. Ecoflex 1:1 appears to be the most similar to the cuttlefish. The k2 values of the Ecoflex are all significantly higher than the cuttlefish fins. Ecoflex 1:3 is the closest in k2 values. The differences between Ecoflex and the cuttlefish fin show also in the relaxation curves in figure 15. The slope of the curve is very similar for both samples. When comparing the different ratios of Ecoflex with the cuttlefish statistically the k1 values show no statistical difference ($p = 0.4$), but k2 is significantly different ($p < 0.005$).

Figure 13

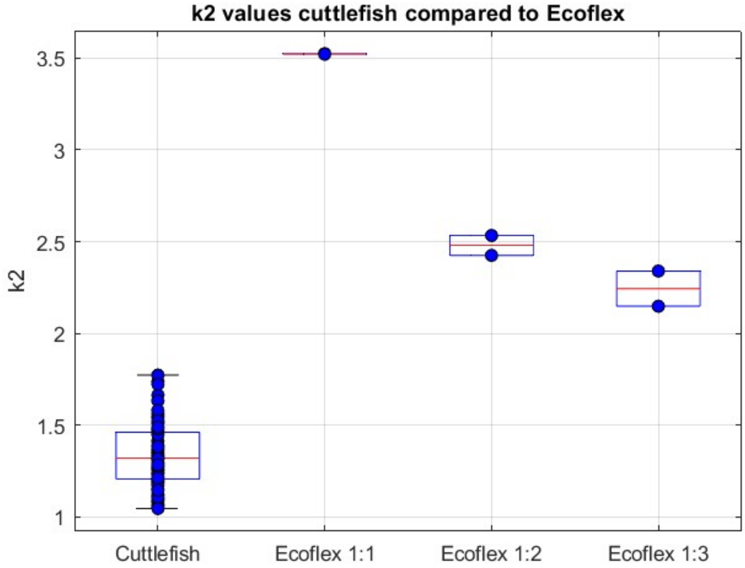
k1 values of Ecoflex 00-10 compared to cuttlefish



* The blue dots represent the individual data points.

Figure 14

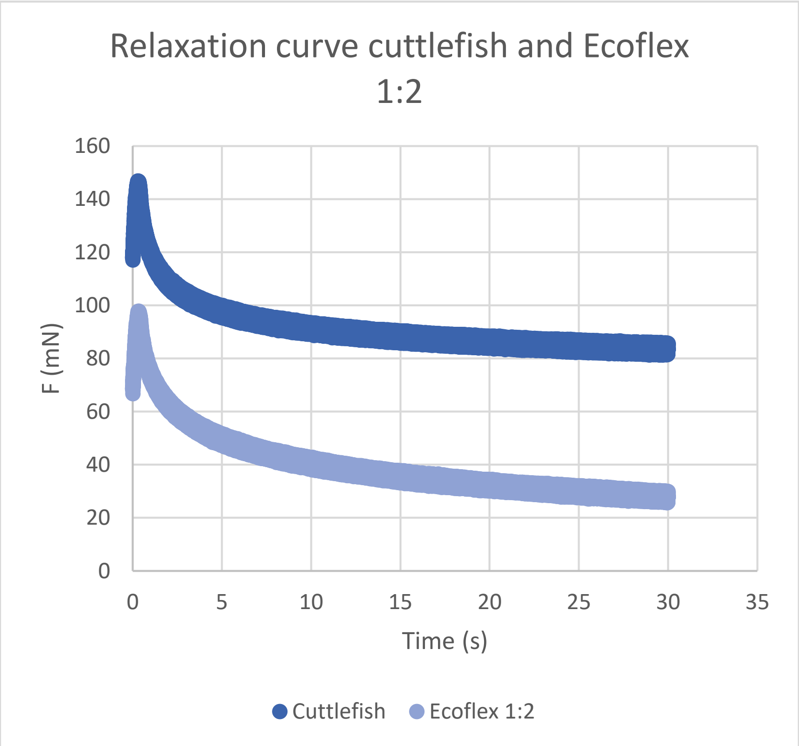
k2 values of Ecoflex 00-10 compared to cuttlefish



* The blue dots represent the individual data points.

Figure 15

Relaxation curve of cuttlefish compared to Ecoflex 00-10 at with a 1:2 ratio



3.3 Influence of water and saline water on the viscoelasticity of the artificial material

After the artificial material was selected and compared to the viscoelasticity of the cuttlefish fin, the material has been tested on the influence of water and salinity. The values for this influence have also been compared to the cuttlefish fin. This has answered the question:' What is the difference in viscoelasticity of the selected artificial material in air, water, and saline water?'.

3.3.1 Influence of water and saline water

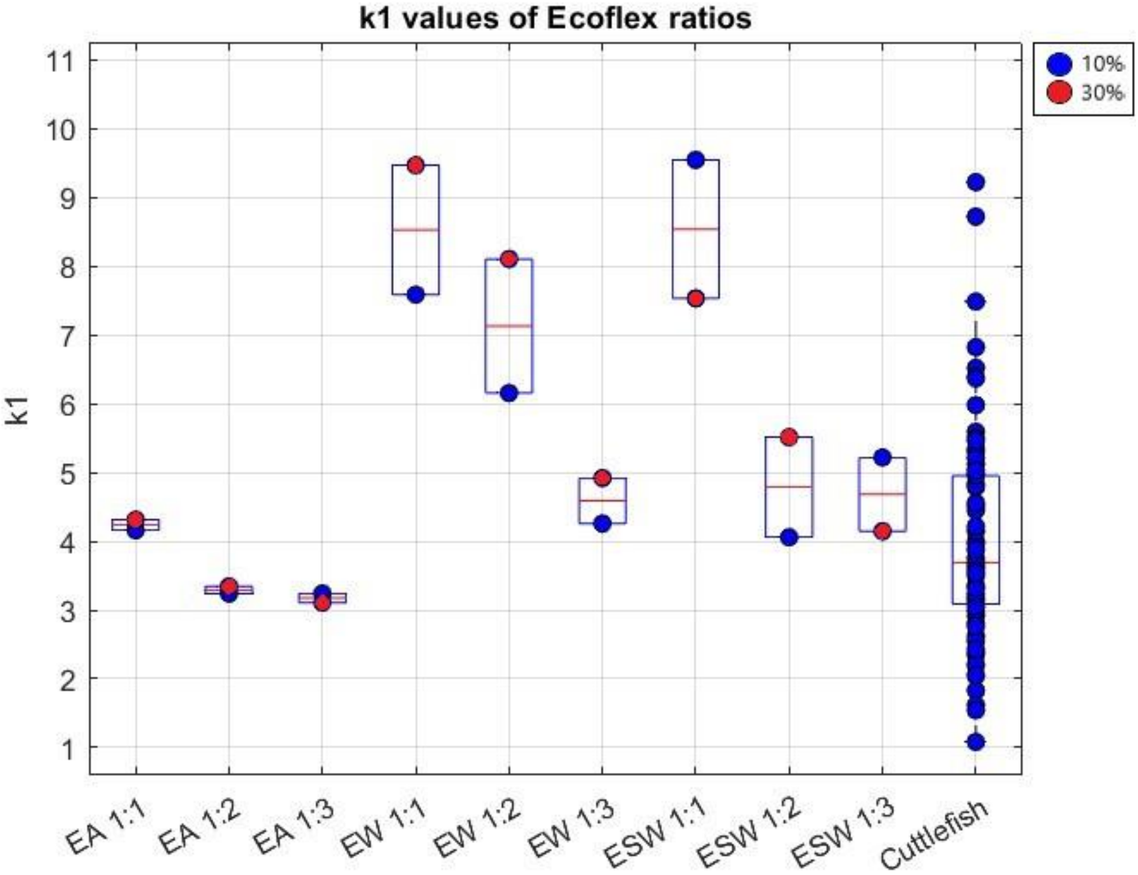
The influence of water and saline water on the viscoelasticity of Ecoflex 00-10 can be seen in figures 16 and 17. In all the graphs it is apparent that the presence of water has increased all values. Also, the salinity in the water seems to be of influence on the Ecoflex. As opposed to showing almost no difference between different strains in dry conditions, in water the strain increase seems to also increase the values. Also, in dry conditions the difference between ratio 1:2 and 1:3 looks rather minimal compared to the difference between these ratios in a wet environment. The pattern of a decrease in value from 1:1 to 1:3 seems to continue except for the value of k1 at 10% strain in saline water where 1:2 is lower than 1:3. Statistical testing shows significant differences ($p < 0.005$) between the Ecoflex samples in different conditions for both k1 and k2 values.

3.3.2 Viscoelasticity of Ecoflex in air, water, and saline water compared to cuttlefish fin

In figures 16 and 17 the cuttlefish fin k values have been compared with the Ecoflex samples that have been exposed to different conditions (air, water, saline water). The k1 values for the cuttlefish fin usually are slightly higher than the dry Ecoflex samples except for Ecoflex 1:1 at 10% strain. In contrast, the k1 values for Ecoflex in water and saline water are all higher than the cuttlefish fin except for Ecoflex 1:3 in saline water at 30% strain. The k1 values seem to be most similar to Ecoflex 1:3 in wet conditions. When dry, the Ecoflex 1:1 shares more similarities with the cuttlefish fin. All k2 values of the Ecoflex 00-10 are higher than the cuttlefish fin average. For all of them Ecoflex 1:3 comes closest to the cuttlefish since those have the lowest values of the Ecoflex. The k2 values at 30% strain are closer to the cuttlefish fin compared to 10% strain. According to statistical analysis there is a significant difference between Ecoflex in different conditions compared to the cuttlefish fin for both k1 and k2 values. However, when specifically looking at Ecoflex with a 1:3 ratio there is no significant difference ($p > 0.05$) found compared to the cuttlefish fins. But the k2 values do show a significant difference ($p < 0.005$) between the two.

Figure 16

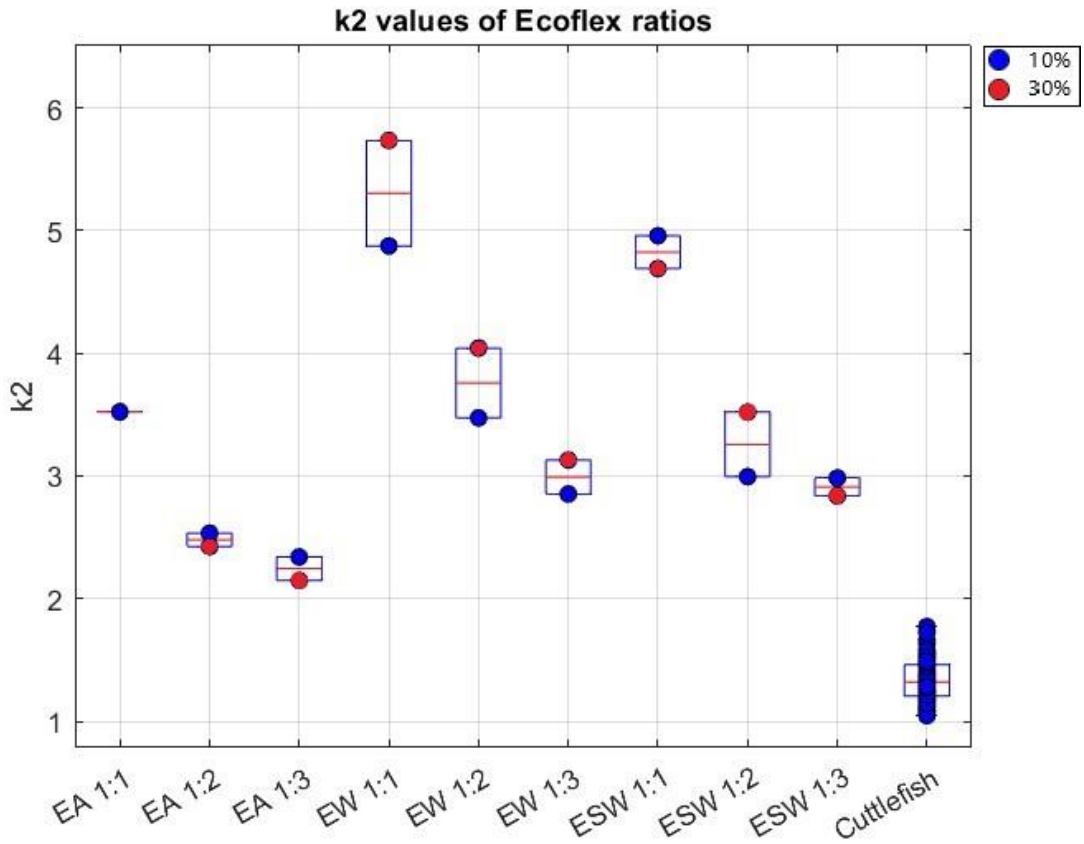
k1 values of Ecoflex 00-10 at different ratios in different environmental conditions (air, water, saline water) + cuttlefish fin



**Labels: EA = Ecoflex 00-10 exposed to air, EW = Ecoflex 00-10 exposed to water, ESW = Ecoflex 00-10 exposed to saline water, Ecoflex dot colors: blue dots = 10% strain, red dots = 30% strain*

Figure 17

k1 values of Ecoflex 00-10 at different ratios in different environmental conditions (air, water, saline water) + cuttlefish fin



**Labels: EA = Ecoflex 00-10 exposed to air, EW = Ecoflex 00-10 exposed to water, ESW = Ecoflex 00-10 exposed to saline water, Ecoflex dot colors: blue dots = 10% strain, red dots = 30% strain*

4. Discussion

In this project the viscoelasticity of the European common cuttlefish fins was measured and compared to Ecoflex 00-10 to get an answer on the question: 'What artificial material(s) has/have the same viscoelastic properties as the European common cuttlefish's (*Sepia officinalis*) lateral fins?'. The goal of answering this question is to be able to produce an artificial material that can recreate the cuttlefish's fin movement and can be used for robotic application. Additionally, the viscoelastic characterization of the cuttlefish and the selected material can be used in subsequent research. In the next two paragraphs a reflection on the used methodology and the results is described.

4.1 Reflection methodology

To answer the first sub-question (What are the viscoelastic properties of the cuttlefish fins?) of this project the first step was to obtain the biological specimens. The specimens had to be as fresh as possible to prevent the influence of rigor mortis on the viscoelastic results. The delivery service looked every morning if there were fresh cuttlefish available for delivery if not then the delivery was canceled. This indicates that the specimens were as fresh as possible, but information on exactly how long ago the cuttlefish were neutralized is not available so influence of rigor mortis cannot be ruled out fully.

Before the specimens were ready for indentation, the thickness of the fin for every indentation point was measured with the measuring device displayed in figure 2. An electric caliper has good precision however the device is self-constructed and must be handled manually so human error cannot be ruled out. An automated method for measuring the tissue thickness perhaps would have been more precise however, this device should give sufficient accuracy. The indentation was performed with a 20g force transducer. In the results, it was apparent that some measurements were unusable due to the peak forces that exuded the 20g force of the transducer. This results in a flat line instead of a peak on the relaxation curve (example in Appendix IV). This could have been prevented by using a stronger force transducer however that would introduce more noise in the measurement which could potentially influence the accuracy of the measurement. Since the peak force of the transducer was only reach a hand full of times the results could be ignored. Preliminary measurements showed that measuring the fins in the water resulted in inaccurate results due to the tissue not being distributed evenly on the surface. This was resolved by measuring the fin out of the water, but the fin was kept and put back into 3.5% saline water to prevent osmotic variation.

After indentation, the results were computed in the Peleg model. This model gives a good representation of the viscoelasticity of the fin and is useful for comparing the fin with artificial material. There are viscoelastic models with higher accuracy than the Peleg model, but this model was very compliable with this research as the goal was to compare viscoelasticity across materials. When looking into the viscoelasticity of the cuttlefish specifically a more precise model would be more appropriate.

To answer the second sub-question (What artificial material shows potential similar viscoelastic behavior as the cuttlefish fins?) of this project the results of the first sub-question were used to select a similar artificial material. The Young's modulus was used to compare the results of the cuttlefish fin with other artificial materials. This parameter is much more popular for comparing material properties with different materials. So, using this parameter opened the possibility of comparing the fin with more materials. Obtaining the Young's modulus with indentation results is not the most accurate but gave a good enough indication without having to do an additional test. The most eligible materials were chosen and investigated further by looking at other parameters and properties that could influence the applicability of robotic usage. Eventually the most eligible material was selected for indentation testing. Perhaps more materials could be considered and measured to have a broader approach to the question. Producing all materials and testing them was too time consuming for the scope of this project. However, the selected material was created with different ratios to have a variation of viscoelastic properties for the same material. So, the selected material has been broadly addressed. The Ecoflex 00-10 has only been measured once, which is a lot less compared to the cuttlefish. This is because Ecoflex 00-10 is a homogenous material since it is artificial, natural material on the other hand is usually heterogeneous, so more measurements are necessary. One measurement of the Ecoflex 00-10 in theory should give an accurate representation of its viscoelasticity with only one measurement.

To answer the final sub-question (What is the difference in viscoelasticity of the selected artificial material in air, water, and saline water?) the Ecoflex 00-10 samples were created three times, one for each of the conditions. The different ratios were made from the same batch over all three conditions to prevent the influence of formulations differences. The samples were exposed to their conditions over the weekend. It has not been measured if there is a difference in viscoelasticity at different time points exposed to the specific environment. However, Ecoflex 00-10 has good stability so should be able to withstand longer durations of water exposure. The cuttlefish lives in the water and was measured by keeping it in 3.5% saline water to avoid osmotic variation, so the influence of water and salinity is important when comparing the viscoelastic behavior of Ecoflex to the cuttlefish fins. Additionally, that is also a requirement for robotic usage.

4.2 Reflection results

The results of the first sub-question (What are the viscoelastic properties of the cuttlefish fins?) show that the k1 values of the cuttlefish fins range mainly between 3 and 5 and the k2 values are close to 1, mainly ranging from 1.2 to 1.5. Compared to viscoelastic data of other natural tissues (Peleg & Normand, 1983) (Thielen et al., 2013) the viscoelasticity of the cuttlefish fin is very comparable to potato flesh. Relative to other materials that are measured the k1 value of the cuttlefish and the potato flesh is significantly lower. A low k1 value means that the material has a lowered relaxation rate. This indicates that the material has more pronounced viscoelastic behavior. The material has a higher viscosity so takes longer to go back to its original shape. The k2 value represents the solidity of the material. A k2 of 1.0 is a liquid material, meaning that all stress relaxes. A k2 value of ∞ means that the material is solid but perfectly elastic which means it will not relax at all. So, the cuttlefish fin is closer to a liquid material where the stress will relax.

When looking at the three cuttlefish that have been measured separately, there is a significant difference found between the specimens when also taking influencing parameters into account. This means that the viscoelasticity of the cuttlefish fins will vary among different individuals. The variation of the viscoelasticity among the fin is found to not be significant indicating a evenly distributed viscoelasticity not influenced by tissue thickness or position on the fin. All measurements have been conducted twice on the same point but with a different pre-set strain. A higher strain percentage means that the indenter will go deeper into the tissue. This could have potentially changed the viscoelasticity of the tissue since more of the tissue is involved in the relaxation process. Since the tissue of the cuttlefish consists of different types and layers this could potentially have

been of influence. Although the increase of strain seems to increase the k values, the difference is found not to be significant. So, the viscoelasticity remains mainly the same when including more of the tissue in the relaxation process.
The second sub-question (What artificial material shows potential similar viscoelastic behavior as the cuttlefish fins?) shows that Ecoflex 00-10 has very similar viscoelastic properties to the cuttlefish as was predicted previously. The material was initially selected because of its similar Young's modulus to the cuttlefish as this is an easier and more mainstream way of comparing the elasticity of materials. Other known material properties like stability and mechanical strength led to the decision of picking Ecoflex over hydrogel. One property that is a slight downside of the material is the stickiness. However, this could potentially be resolved with additives in the formulation or topically applying an anti-sticking agent.

The material has been tested at three different ratios of chemical composition. This showed a significant difference between the different ratios for both k1 and k2 values. Ecoflex 1:1 has a k1 of 4.2 and a k2 of 3.5, Ecoflex 1:2 has a k1 of 3.3 and a k2 of 2.5, and Ecoflex 1:3 has a k1 of 3.2 and a k2 of 2.2. The preliminary study done by WUR (personal communication, 22 March 2023) has measured the viscoelastic properties of Ecoflex 00-30. The k1 values for this material mainly ranged between 60 and 80 and for the k2 values around 20. So, the Ecoflex viscoelasticity drops significantly with a drop in shore hardness. The k values of the Ecoflex indicates the material being a lot more viscous and closer to liquid just like the cuttlefish. Actually, in terms of k1 values there has no significant difference been found between the ratios of Ecoflex 00-10 compared to the cuttlefish fins. However, there is a significant difference between the k2 values of the Ecoflex and the cuttlefish. This suggests that Ecoflex 00-10 has a similar relaxation rate to the cuttlefish and exhibits viscosity similar to the cuttlefish. But the solidity of the material is different from the cuttlefish.

The results of the third sub-question (What is the difference in viscoelasticity of the selected artificial material in air, water, and saline water?) indicate that there is a significant influence of water and saline water on the viscoelasticity of the Ecoflex 00-10. So prolonged exposure of an aqueous environment does influence the viscoelastic behavior of the Ecoflex. When comparing the k1 and k2 values of the Ecoflex in different conditions to the cuttlefish, the water seemed to have distanced the k values of the Ecoflex compared to the cuttlefish even more. But when specifically focusing on the Ecoflex 1:3 samples, water seems to not be of too much influence since there is no significant difference between the Ecoflex and the cuttlefish at this ratio. Since the Ecoflex 1:3 in saline water samples have been exposed to the same conditions and still show similar viscoelastic behavior this ratio seems to be most comparable to the cuttlefish. The k2 values however do still differ significantly.

5. Conclusion and recommendations

The goal of this project was to find a bio-inspired material that mimics the viscoelastic behavior of the European common cuttlefish's lateral fins so the material can be used for soft robotic application. This goal has been reached by answering the main research question of this project: 'What artificial material has the same viscoelastic properties as the European common cuttlefish's (*Sepia officinalis*) lateral fins?'. This question is divided into sub-questions which will be answered in this chapter and subsequently an answer on the main research question is given. Finally, some recommendations for future research and robotic application are described.

5.1 What are the viscoelastic properties of cuttlefish fins?

The viscoelastic properties of cuttlefish fins can be described by having a relatively low relaxation time and being very close to a liquid material in which all stress relaxes compared to other natural materials. The viscoelastic behavior will differ depending on the individual but there is no significant variation of the viscoelastic properties across the fins of an individual. Moreover, there is only a slight increase in the viscoelastic properties when taking more of the tissue into consideration.

5.2 What artificial material shows potential similar viscoelastic behavior as the cuttlefish fins?

It was found that Ecoflex 00-10 shows the potential of showing similar viscoelastic behavior as the cuttlefish fins. The two materials share a similar Young's moduli indicating similar elasticity between the Ecoflex and the cuttlefish fin. The viscoelasticity of the material is very customizable by adjusting the ratio of its chemical composition or with the addition of additives. The difference in viscoelasticity across the different ratios can account for the variation of viscoelasticity found in cuttlefish. However, this only applies to the relaxation time of the material. The solidity of the material is significantly different. Nevertheless, when comparing the difference of solidity to other materials the difference between the Ecoflex and the cuttlefish does not differ as much as with others.

5.3 What is the difference in viscoelasticity of the selected artificial material in air, water, and saline water?

The introduction of water and saline water has a significant difference on the viscoelasticity of the Ecoflex. Both k values increase when exposed to water, which makes it exceed the k values of the cuttlefish significantly. The viscoelasticity of the Ecoflex after subjection to water now shows a significant difference between the Ecoflex and the cuttlefish fins. However, when comparing only the Ecoflex with a ratio of 1:3 there is no significant difference between de Ecoflex and the cuttlefish fins again.

5.4 What artificial material has the same viscoelastic properties as the European common cuttlefish's (Sepia officinalis) lateral fins?

When comparing the viscoelastic properties of the European common cuttlefish's lateral fins with the tested artificial material Ecoflex 00-10 it can be concluded that Ecoflex with a ratio of 1:3 has the most similar viscoelastic behavior to the cuttlefish fins even after exposure to saline water. This ratio of Ecoflex 00-10 resembles the measurement of the cuttlefish fins the most and still is not significantly different in terms of its relaxation speed. The solidity does differ from the cuttlefish however relative to the k2 values of other materials the solidity difference is negligible. These findings show applicability of Ecoflex 00-10 at ratio 1:3 to be usable for robotic application.

5.5 Recommendations

To improve upon these findings there are some recommendations for future research and application of Ecoflex in soft robotics. The recommendations are divided by short term and long-term recommendations.

5.5.1 Short term recommendations

Recommendations on short term future research include doing more research on the viscoelastic behavior of the cuttlefish, perhaps by computing the raw data with a more specific viscoelastic model so the exact viscoelastic behavior of the cuttlefish fins can be determined. Additionally, Ecoflex 00-10 could be investigated deeper by introducing for example chemical additives into the formulation to mimic the cuttlefish fins to the fullest extent. Short term recommendations on the robotic application of the material would include finding a solution for the stickiness of the material.

5.5.2 Long term recommendations

Long term recommendations on future research includes investigating the viscoelasticity across species and investigating other attributions that influence the biomechanics of the cuttlefish fins. For robotic application the other factors that influence the fin movement should be adjusted accordingly.

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Appendix I MATLAB code for indentation testing

```
%% INTITAL SETTINGS FOR THE EXPERIMENT
CONST.name = '20230728_HG10_p2_05'
Group = 'C:\Users\Teacher\Desktop\Indenter_script\Daans_fins\';

% Experiment
CONST.rep = 1;                      % repetitions []
% CONST.diam = 1;                    % probe diameter [mm]

% Movement
CONST.disp_max = 25;                 % total displacement [mm] (BK: Don't change
this. Default: 25)
CONST.ind_dep = 0.2;                % desired indentation depth [mm] (Thickness of
sample in mm /10!!!!)
CONST.ind_ret = 1;                 % retraction distance [mm]
CONST.vel = 0.5;                     % indentation speed [mm s^-1]
CONST.vel_max = 2;                   % homing speed [mm s^-1]
CONST.max = CONST.disp_max;                      % max. retraction, home position
[mm]

% Measurement
CONST.rate = 1000;                   % measurement frequency [Hz]
CONST.dur_zero = 10;                 % measurement duration for zero measurement
[s]
CONST.dur_rest = 30;                 % measurement duration for resting measurement
[s]
CONST.dur_meas = 0.01;               % measurement duration for measurement [s]
CONST.t_paus = 10;                    % Pause between indentation and retraction
[s]
CONST.volt_mult = 1;                 % mN -> N conversion
CONST.cal = 0.143777802488417 * 1000; % Calibration [mN/mV] - 100 g load cell

% Others
CONST.paus = 1.5;
CONST.contact_force = 10;           % critical load to detect contact [mN] (BK:
This may need to change based on the sensitivity of the transducer (2 for 20 gram,
5 for 100 gram)
CONST.abort_force = 800;             % max. allowed load [mN]
CONST.buffer = 1000;                 % size of buffer array

%% Preparations

s.Rate = CONST.rate;

disp('Move to zero...');

% Set fast speed
f.SetVelParams(0,0,2,CONST.vel_max);
% Set stage to max. retraction
if f.GetPosition_Position(0) ~= CONST.max
    f.SetAbsMovePos(0,CONST.max);
    f.MoveAbsolute(0,1==0);
    % Wait
    pos = f.GetPosition_Position(0);
    while abs(pos - CONST.max) > 0.0001
       pos = f.GetPosition_Position(0);
       pause(CONST.paus);
    end
```

```
end

% Preallocation
t1 = [0];
t2 = [0];
pos = [0];
for i = 1:CONST.rep
    index(i) = 1;                                                     %
measurement index
    DATA.rep(i).volt_zero(1:CONST.rate*CONST.dur_zero) = [0];
    DATA.rep(i).volt_zero_mean = [0];
    DATA.rep(i).volt(1:CONST.rate*CONST.dur_meas,1:CONST.buffer) = [0];
    DATA.rep(i).volt_mean(1,1:CONST.buffer) = [0];
    DATA.rep(i).forc(1,1:CONST.buffer) = [0];
    DATA.rep(i).dist(1,1:CONST.buffer) = [0];
    DATA.rep(i).time(1,1:CONST.buffer) = [0];
    DATA.rep(i).dist_cont = [0];
    DATA.rep(i).ind_rev = [0];
end

%% Measurements
profile on;
% i... repetition
for i = 1:CONST.rep
% Zero force signal, long measurement
    tic;
    t1 = toc;
    s.DurationInSeconds = CONST.dur_zero;
    DATA.rep(i).volt_zero = startForeground(s);
    DATA.rep(i).volt_zero_mean = mean(DATA.rep(i).volt_zero) * CONST.volt_mult;

    disp('Zero signal');

% Set short measurements
    s.DurationInSeconds = CONST.dur_meas;

    if i == 1
% Set slow approach speed
        f.SetVelParams(0,0,2,CONST.vel);

% Measure 1st data point, 0 force
        DATA.rep(i).volt(:,index(i)) = startForeground(s);
        DATA.rep(i).volt_mean(index(i)) = mean(DATA.rep(i).volt(:,index(i))) *
CONST.volt_mult;
        DATA.rep(i).forc(index(i)) = (DATA.rep(i).volt_mean(index(i)) -
DATA.rep(i).volt_zero_mean) * CONST.cal;       % Compute force relative to zero
measurement [mN]
        DATA.rep(i).dist(index(i)) = f.GetPosition_Position(0);
        DATA.rep(i).time(index(i)) = toc;
        disp('Indent slowly');

    elseif i > 1
% Fast approach
        disp('Approach');
        f.SetVelParams(0,0,2,CONST.vel_max);
        f.SetAbsMovePos(0,DATA.rep(i-1).dist_cont+CONST.ind_ret);
        f.MoveAbsolute(0,1==0);
% Wait
        pos = f.GetPosition_Position(0);
```

```
%          while pos ~= DATA.rep(i-1).dist_cont+CONST.ind_ret
%              pos = f.GetPosition_Position(0);
%              pause(CONST.paus);
%          end

        while abs(pos - (DATA.rep(i-1).dist_cont+CONST.ind_ret)) > 10^(-3)
            pos = f.GetPosition_Position(0);
            pause(CONST.paus);
        end

% Set slow approach speed
        f.SetVelParams(0,0,2,CONST.vel);

% Measure 1st data point, 0 force
        DATA.rep(i).volt(:,index(i)) = startForeground(s);
        DATA.rep(i).volt_mean(index(i)) = mean(DATA.rep(i).volt(:,index(i))) *
CONST.volt_mult;
        DATA.rep(i).forc(index(i)) = (DATA.rep(i).volt_mean(index(i)) -
DATA.rep(i).volt_zero_mean) * CONST.cal;       % Compute force relative to zero
measurement [mN]
        DATA.rep(i).dist(index(i)) = f.GetPosition_Position(0);
        DATA.rep(i).time(index(i)) = toc;
        disp('Indent slowly');
    end

% Start indentation
        f.SetAbsMovePos(0,CONST.max-CONST.disp_max);
        f.MoveAbsolute(0,1==0);

% Indent up to desired max. distance
    while f.GetPosition_Position(0) >= CONST.max-CONST.disp_max
% Approach object as long as no contact force is detected
        while abs(DATA.rep(i).forc(index(i))) <= CONST.contact_force
% Emergency abort
            if abs(DATA.rep(i).forc(index(i))) >= CONST.abort_force
                f.StopImmediate(0);
                disp('Emergency abort');
                break;
            end
            if f.GetPosition_Position(0) <= CONST.max-CONST.disp_max
                disp('Max. indentation reached');
                break;
            end
            index(i) = index(i) + 1;
            DATA.rep(i).volt(:,index(i)) = startForeground(s);
% Voltage sequence
            DATA.rep(i).volt_mean(index(i)) = mean(DATA.rep(i).volt(:,index(i))) *
CONST.volt_mult;                                   % Average voltage
            DATA.rep(i).forc(index(i)) = (DATA.rep(i).volt_mean(index(i)) -
DATA.rep(i).volt_zero_mean) * CONST.cal;     % Force [mN]
            DATA.rep(i).dist(index(i)) = f.GetPosition_Position(0);
% Displacement
            DATA.rep(i).time(index(i)) =
toc;
% Time
        end
        disp('Contact detected');
% If contact force is detected, save current position
        DATA.rep(i).dist_cont = DATA.rep(i).dist(index(i));
```

```
% Continue approach for desired distance
        while f.GetPosition_Position(0) >= DATA.rep(i).dist_cont-CONST.ind_dep
% Emergency abort, stop immediately
            if abs(DATA.rep(i).forc(index(i))) >= CONST.abort_force
                f.StopImmediate(0);
                disp('Emergency abort');
                break;
            end
            if f.GetPosition_Position(0) <= CONST.max-CONST.disp_max
                disp('Max. indentation reached');
                break;
            end
            index(i) = index(i) + 1;
            DATA.rep(i).volt(:,index(i)) = startForeground(s);
% Voltage sequence
            DATA.rep(i).volt_mean(index(i)) = mean(DATA.rep(i).volt(:,index(i))) *
CONST.volt_mult;                               % Average voltage
            DATA.rep(i).forc(index(i)) = (DATA.rep(i).volt_mean(index(i)) -
DATA.rep(i).volt_zero_mean) * CONST.cal;       % Force [mN]
            DATA.rep(i).dist(index(i)) = f.GetPosition_Position(0);
% Displacement
            DATA.rep(i).time(index(i)) = toc;
        end
% If desired indentation depth is reached, stop controlledly
        f.StopProfiled(0);
%         pause(CONST.paus);
        disp('Reverse direction');
        break;
    end

    s.DurationInSeconds = CONST.dur_rest;
    volt_rest = startForeground(s);
    force_rest = -(volt_rest - DATA.rep(i).volt_zero_mean) * CONST.cal;
    time_rest = linspace(0,CONST.dur_rest,CONST.dur_rest*CONST.rate)';

% Save index of max. indentation
    DATA.rep(i).ind_rev = index(i);
% Wait for specified time
%     index(i) = index(i) + 1;
%     DATA.rep(i).volt(:,index(i)) = startForeground(s);
% Voltage sequence
%     DATA.rep(i).volt_mean(index(i)) = mean(DATA.rep(i).volt(:,index(i))) *
CONST.volt_mult;                               % Average voltage
%     DATA.rep(i).forc(index(i)) = (DATA.rep(i).volt_mean(index(i)) -
DATA.rep(i).volt_zero_mean) * CONST.cal;       % Force [mN]
%     DATA.rep(i).dist(index(i)) = f.GetPosition_Position(0);
% Displacement
%     DATA.rep(i).time(index(i)) = toc;

%     pause(CONST.t_paus-CONST.paus);

    s.DurationInSeconds = CONST.dur_meas;

% Start slow retraction up to specified distance rel. to contact distance
    f.SetAbsMovePos(0,DATA.rep(i).dist_cont+CONST.ind_ret);
    f.MoveAbsolute(0,1==0);

    while f.GetPosition_Position(0) <= DATA.rep(i).dist_cont+CONST.ind_ret
% Emergency abort
```

```
        if abs(DATA.rep(i).forc(index(i))) >= CONST.abort_force
            f.StopImmediate(0);
            break;
        end
        index(i) = index(i) + 1;
        DATA.rep(i).volt(:,index(i)) = startForeground(s);
        DATA.rep(i).volt_mean(index(i)) = mean(DATA.rep(i).volt(:,index(i))) *
CONST.volt_mult;
        DATA.rep(i).forc(index(i)) = (DATA.rep(i).volt_mean(index(i)) -
DATA.rep(i).volt_zero_mean) * CONST.cal;
        DATA.rep(i).dist(index(i)) = f.GetPosition_Position(0);
        DATA.rep(i).time(index(i)) = toc;
    end
    f.StopProfiled(0);
    pause(CONST.paus);

% Return fast to home position
    f.SetVelParams(0,0,2,CONST.vel_max);
    f.SetAbsMovePos(0,CONST.max);
    f.MoveAbsolute(0,1==0);
% Wait
    pos = f.GetPosition_Position(0);
    while pos ~= CONST.max
        pos = f.GetPosition_Position(0);
        pause(CONST.paus);
    end

% Display progress in the command window
    t2 = toc;
    out = ['Repetion ' num2str(i) '/' num2str(CONST.rep) ' finished... \nDuration
= ' num2str(t2-t1) ' s... \nRemaining time = ' num2str(((CONST.rep-i)*t2-t1)/60) '
m...'];
    disp(sprintf(out));
end

profile viewer;

%% Post-processing

% Delete over-allocated values
for i = 1:CONST.rep
    DATA.rep(i).volt_mean(index(i)+1:CONST.buffer) = [];
    DATA.rep(i).forc(index(i)+1:CONST.buffer) = [];
    DATA.rep(i).dist(index(i)+1:CONST.buffer) = [];
    DATA.rep(i).time(index(i)+1:CONST.buffer) = [];
end

% Check time steps
for i = 1:CONST.rep
    DATA.rep(i).dt = diff(DATA.rep(i).time);
end

%% +++ Plotting
fig_2 = figure();
% repetition color coding:
% black -> white, 1st -> last repetition
for i = 1:CONST.rep
    level = (CONST.rep-i)/CONST.rep*0.95;
    Color(i,:) = [level*255/255 level*255/255 level*255/255];
```

```
end

% Force - distance
sub_1 = subplot(3,1,1);
hold all;
for i = 1:CONST.rep

plot(DATA.rep(i).dist(1:DATA.rep(i).ind_rev),DATA.rep(i).forc(1:DATA.rep(i).ind_re
v),'--x','Color',Color(i,:),'MarkerSize',2);

plot(DATA.rep(i).dist(DATA.rep(i).ind_rev+1:end),DATA.rep(i).forc(DATA.rep(i).ind_
rev+1:end),':o','Color',Color(i,:),'MarkerSize',2);
end
for i = 1:CONST.rep
    plot([DATA.rep(i).dist_cont DATA.rep(i).dist_cont],sub_1.YLim,'--
','Color',Color(i,:));
end
hold off
xlabel('Distance [mm]')
ylabel('Normal force [mN]')
% Force - time
subplot(3,1,2);
hold all;
for i = 1:CONST.rep

plot(DATA.rep(i).time(1:DATA.rep(i).ind_rev),DATA.rep(i).forc(1:DATA.rep(i).ind_re
v),'--x','Color',Color(i,:),'MarkerSize',2);

plot(DATA.rep(i).time(DATA.rep(i).ind_rev+1:end),DATA.rep(i).forc(DATA.rep(i).ind_
rev+1:end),':o','Color',Color(i,:),'MarkerSize',2);
end
xlabel('Time [s]');
ylabel('Normal force [mN]');
hold off;
% Distance - time
subplot(3,1,3);
hold all;
for i = 1:CONST.rep

plot(DATA.rep(i).time(1:DATA.rep(i).ind_rev),DATA.rep(i).dist(1:DATA.rep(i).ind_re
v),'--x','Color',Color(i,:),'MarkerSize',2);

plot(DATA.rep(i).time(DATA.rep(i).ind_rev+1:end),DATA.rep(i).dist(DATA.rep(i).ind_
rev+1:end),':o','Color',Color(i,:),'MarkerSize',2);
end
xlabel('Time [s]');
ylabel('Distance [mm]');
hold off;

figure;
plot(time_rest,force_rest);


%% +++ Saving
M(:,1) = time_rest;
M(:,2) = force_rest;
dlmwrite([Group CONST.name '.csv'],M,'delimiter','\t');

clear M
```

```
% Time steps
% fig_3 = figure();
% hold all
% for i = 1:CONST.rep
%     plot(DATA.rep(i).dist(1:end-
1),DATA.rep(i).dt,'x','Color',Color(i,:),'MarkerSize',2);
% end
% hold off
% xlabel('Distance [mm]');
% ylabel('Time step [s]');
% set(gca, 'YLim', [0 0.5]);

% fig_4 = figure();
% hold all
% for i = 1:CONST.rep
%     plot(DATA.rep(i).dt,'x','Color',Color(i,:),'MarkerSize',2);
% end
% hold off
% xlabel('Index []');
% ylabel('Time step [s]');
% set(gca, 'YLim', [0 0.5]);

% +++ Saving
filename = [Group CONST.name];
save(filename);
% saveas(fig_2,filename,'fig');
% saveas(fig_2,filename,'png');

% for i = 1:CONST.rep
%     M(:,1) = DATA.rep(i).time;
%     M(:,2) = DATA.rep(i).dist;
%     M(:,3) = DATA.rep(i).forc;
%     dlmwrite([Group CONST.name sprintf('_%d.csv', i)],M,'delimiter','\t');
%
%     clear M
% end

% %% +++ Test measurement speeds
% close all;
% clear test testrate testdur testtime;
% testrate = linspace(100,10000,10);
% testdur = linspace(0.0001,0.01,10);
% for i = 1:size(testrate,2)
%     i
%     s.Rate = testrate(i);
%     for j = 1:size(testdur,2)
%         s.DurationInSeconds = testdur(j);
%         for k = 1:10
%             tic;
%             test(i,j).data(:,k) = startForeground(s);
%             test(i,j).time(k) = toc;
%         end
%         testtime(i,j) = mean(test(i,j).time(:));
%     end
% end
% figure();
% hold all;
%     surf(testdur*1000,testrate,testtime*1000);
```

```
%     xlabel('duration [ms]');
%     ylabel('rate [Hz]');
%     zlabel('real time [ms]');
% hold off
% figure();
% hold all;
%     surf(testdur*1000,testrate,testtime./testdur);
%     surf(testdur*1000,testrate,ones(size(testrate,2),size(testdur,2)));
%     xlabel('duration [ms]');
%     ylabel('rate [Hz]');
%     zlabel('ratio, real to planned [-]');
%     zlim([0.9 10]);
%     set(gca, 'ZScale', 'log');
%     set(gca, 'ZTick', [1 1.2 1.5 1.8 2 5 10]);
% hold off
```

Appendix II MATLAB code for Peleg model

```
%% 2023-06-22

clear all
close all

files = dir('*.mat');   % load all .mat files

k1 = NaN(length(files),1);
k2 = NaN(length(files),1);
R2 = NaN(length(files),1);
F{1,1} = 'fin';
F{1,2} = 'point';
F{1,3} = 'strain percent';
F{1,4} = 'k1';
F{1,5} = 'k2';
F{1,6} = 'R2';
F{1,7} = 'time';
F{1,8} = 'force';
F{1,9} = 'force filtered';

for ii=1:length(files)
    % load MAT file
    load(join([files(ii).folder,'/',files(ii).name]));
    close all

    % read fin, point, and strain from filename
    F{ii+1,1} = str2double(files(ii).name(end-9));
    F{ii+1,2} = str2double(files(ii).name(end-7));
    F{ii+1,3} = str2double(files(ii).name(end-6:end-5));

    % read time and force
    F{ii+1,7} = linspace(0,CONST.dur_rest,length(force_rest))';
    F{ii+1,8} = force_rest;

    % for filtering (5th order Butterworth lowpass)
    Fs = CONST.rate; % sampling frequency
    fn = 5; % cutoff frequency
    [y, x] = butter(5, fn/(Fs/2));

    % calculating k1, k2 for Peleg model
    t = linspace(0,CONST.dur_rest,length(force_rest))';
    L = (force_rest(1).*t)./(force_rest(1)-force_rest);
    idx = isfinite(L);
    [p,S] = polyfit(t(idx),L(idx),1);
    k1(ii) = p(1,2);
    k2(ii) = p(1,1);
    F{ii+1,4} = p(1,2);
    F{ii+1,5} = p(1,1);

    % getting R^2 value for linear fit
    R2(ii) = 1 - (S.normr/norm(L(idx) - mean(L(idx))))^2;
    F{ii+1,6} = 1 - (S.normr/norm(L(idx) - mean(L(idx))))^2;

    % saving filtered force
    F{ii+1,9} = filtfilt(y, x,force_rest);
end
```

Appendix III Peleg model results

Cuttlefish	Point	Strain %	k1	k2	R2
1	1	10	3.327788	1.31315	0.996331
1	1	30	11.34521	1.072948	0.090563
1	2	10	1.083938	1.060737	0.999113
1	2	30	2.811895	1.068581	0.999172
1	3	10	3.32241	1.347118	0.995272
1	3	30	3.342888	1.231398	0.997988
1	4	10	2.352438	1.084189	0.999123
1	4	30	6.284038	1.171514	0.802738
1	5	10	4.158511	1.334395	0.995474
1	5	30	3.61932	1.242906	0.996393
1	6	10	2.041342	1.053066	0.999499
1	6	30	3.122157	1.197725	0.779242
1	7	10	3.69747	1.290388	0.997241
1	7	30	5.542523	1.199239	0.451624
1	8	10	2.549791	1.102135	0.998964
1	8	30	3.993234	1.335888	0.995902
1	9	10	3.577656	1.348004	0.997447
1	9	30	4.785565	1.354093	0.996959
1	10	10	2.196542	1.110826	0.999263
1	10	30	4.619587	1.247618	0.830358
1	11	10	2.619233	1.266315	0.998291
1	11	30	3.758703	1.312329	0.997593
1	12	10	2.917395	1.151738	0.999217
1	12	30	53.47144	0.747812	0.000342
1	13	10	2.044251	1.188018	0.997581
1	13	30	78.98173	-1.36372	0.000542
1	14	10	1.830846	1.113421	0.998863
1	14	30	3.582361	1.199045	0.999304
1	15	10	2.394183	1.184637	0.998505
1	15	30	3.354152	1.260253	0.995545
1	16	10	1.618679	1.123047	0.997591
1	16	30	3.160071	1.198859	0.998615
1	17	10	5.304159	1.239994	0.99711
1	17	30	6.518173	1.36863	0.954299
1	18	10	6.818843	1.272546	0.996447
1	18	30	1.54393	1.664488	0.999523
2	1	10	6.384454	1.773211	0.991732
2	1	30	9.217311	1.736557	0.992029
2	2	10	6.363683	1.461757	0.987817
2	2	30	5.975371	1.551729	0.993726
2	3	10	2.559073	1.256115	0.999257
2	3	30	8.005496	1.236161	0.09896
2	4	10	4.515774	1.459797	0.988557

2	4	30	4.832095	1.390193	0.990908
2	5	10	4.491741	1.296607	0.994372
2	5	30	5.588488	1.330598	0.981104
2	6	10	4.541478	1.390363	0.994522
2	6	30	8.715295	1.540542	0.979891
2	7	10	3.132997	1.09434	0.998778
2	7	30	6.3631	1.204824	0.611864
2	8	10	3.962561	1.36668	0.993038
2	8	30	3.870455	1.263657	0.997186
2	9	10	3.639058	1.192305	0.998378
2	9	30	18.39638	0.964462	0.004536
2	10	10	4.143461	1.195403	0.997057
2	10	30	4.805784	1.216146	0.996887
2	11	10	2.210241	1.108496	0.991043
2	11	30	3.183664	1.272684	0.998676
2	12	10	2.052083	1.046401	0.998774
2	12	30	2.987167	1.172924	0.998838
2	13	10	3.041899	1.145684	0.995768
2	13	30	3.233129	1.239476	0.996153
2	14	10	3.334591	1.213366	0.998474
2	14	30	4.984946	1.295279	0.996673
2	15	10	5.118252	1.632982	0.994599
2	15	30	4.94941	1.565	0.994366
3	1	10	3.879886	1.4608	0.996344
3	1	30	5.027444	1.510468	0.995819
3	2	10	5.498183	1.413736	0.995327
3	2	30	3.498881	1.337024	0.997382
3	3	10	5.33817	1.516226	0.994674
3	3	30	3.325653	1.489052	0.99158
3	4	10	5.462413	1.771285	0.993818
3	4	30	7.482298	1.58098	0.993479
3	5	10	4.558676	1.523606	0.99187
3	5	30	5.205703	1.471295	0.995296
3	6	10	3.672866	1.46169	0.997825
3	6	30	5.210869	1.388722	0.994737
3	7	10	3.545624	1.385653	0.989797
3	7	30	2.424757	1.323025	0.99928
3	8	10	4.953665	1.52344	0.993714
3	8	30	4.44763	1.317672	0.997491
3	9	10	3.313636	1.383023	0.994725
3	9	30	3.584179	1.274951	0.998342
3	10	10	2.762444	1.28448	0.995796
3	10	30	4.214479	1.473531	0.996564
3	11	10	3.885972	1.448714	0.992769
3	11	30	4.548909	1.480087	0.997699
3	12	10	3.535884	1.490691	0.972601

3	12	30	5.028625	1.722706	0.994423

Appendix IV: Faulty measurement example