Developing Tunable Viscoelastic Silicone Gel-Based Inks for Precise 3D Printing of Clinical Phantoms

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Supplementary information

Preparation of silicone-based formulations

Table S1. Quantities of the compounds for each silicone-based formulation.

	g Silicone oil / g Silicone	Aerosil g/g
SS0.5	0.5	0
SSA0.5	0.5	0.05
SS1.8	1.8	0
SSA1.8	1.8	0.05
SS7	7	0
SSA7	7	0.05
SSA0	0	0.05
SSA10	10	0.05

Stability study of silicone formulations

A study to evaluate the loss of silicone oil for 50 days was performed to determine if the silicone formulations were stable at long times. As it is shown in Figure S1, as expected formulation without silicone oil (SS0) does not present weight loss and works as a control. Formulations with low content of silicone oil (SS0.5 and SSA0,5) present less than 0.1% of weight loss. However, while formulations that have high content of silicone oil and do not present Aerosil in the mixture (SS1.8 and SS7), after 50 days, they loss almost 1% and 4% of weight loss, the same formulations with Aerosil, present losses of 10 times lower than without Aerosil. Thus, Aerosil contributes on minimizing silicone oil content, obtaining formulations stable and long-term usefulness.
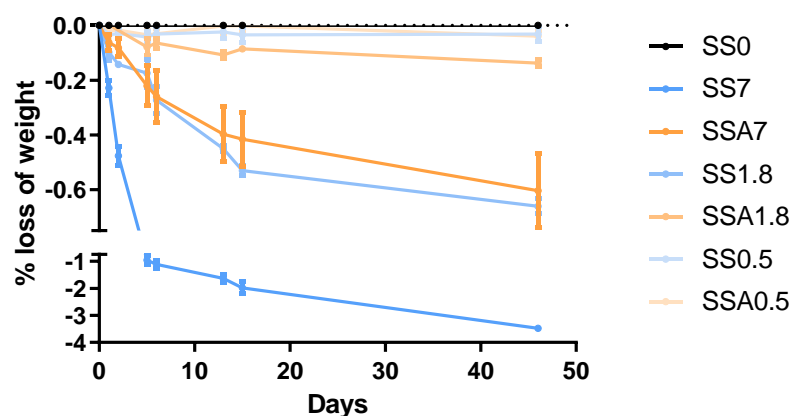
Figure S1. Loss of weight as a function of Aerosil content and time.

Aerosil content

As seen in the paper, Aerosil content has been key to display printable properties for our silicone-based formulations. Other Aerosil content (0.01 g/g) has been studied to ensure optimization of the quantity of this component.

As show in Figure S2 rheological properties and resolution quantification of formulations with this Aerosil content show that 0.01g/g of Aerosil content is not enough to display shear thinning behaviour, recoverability, and uniform filament extrusion.
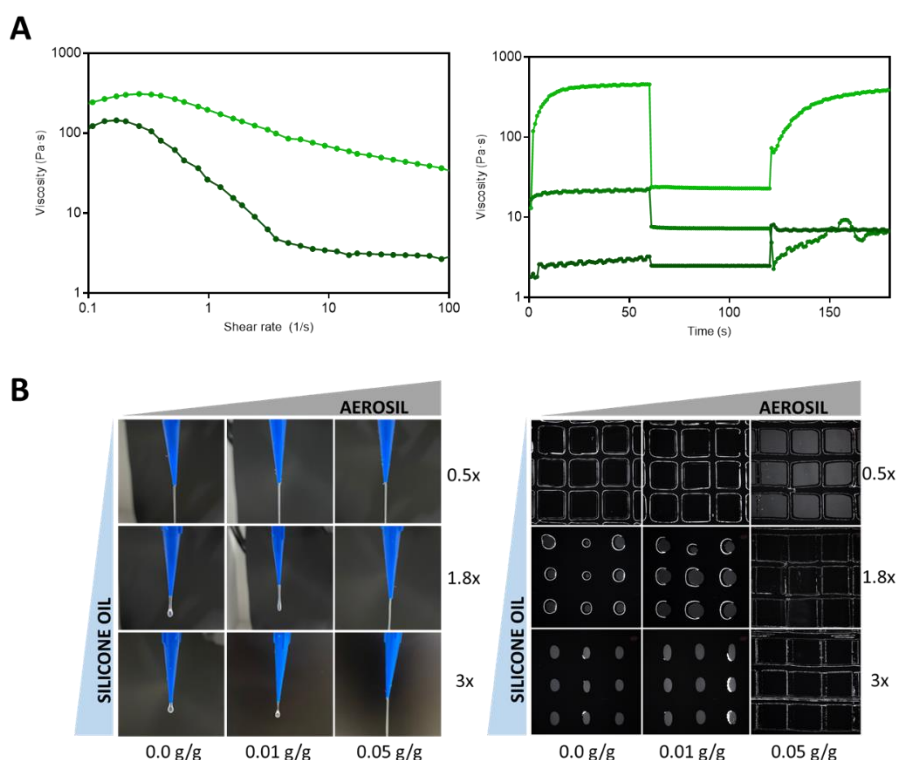

Figure S2. Printability assessment of formulations with 0.01g/g of Aerosil. (A) Rheological properties of silicone-based formulations with 0.01g/g of Aerosil. (B) Filament extrusion and 3D printed lattice to assess printability of the formulations.

DMA analysis of the cured 3D printed samples (Figure S3) show that these formulations present a viscoelastic behaviour with moduli values between the formulations without Aerosil and the ones that have 0.05g/g, as expected.
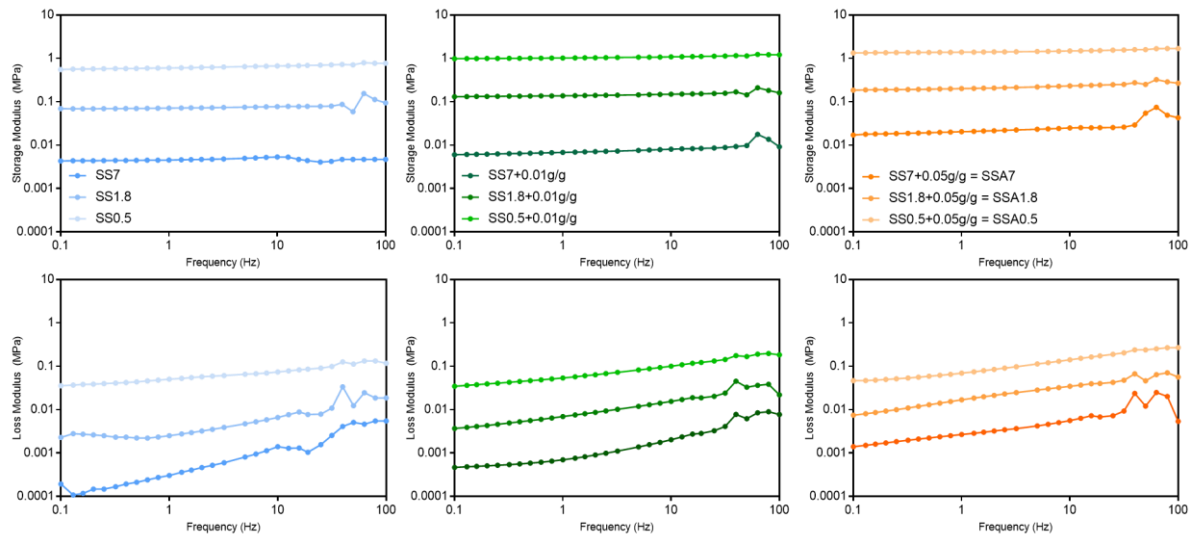

Figure S3. Comparison of DMA analysis of silicone formulations with different content of Aerosil. SS formulations without Aerosil are represented with blue palette, SS formulation with 0.01g/g of Aerosil are represented with green palette, and finally, SSA formulations (0.05g/g of Aerosil) are represented in orange palette.

Clinical validation

Clinical validation questionary S1. Study protocol on the behaviour of new silicones to mimic soft tissues developed by Sant Joan de Déu Hospital.

Purpose and objectives of the study

The purpose of this study is to improve the materials currently used in surgical practice.

The general objective is to evaluate the behaviour of different silicones in the practice of suturing and cutting and determine if they are realistic to live tissues for surgical practice.

The specific objective is to determine which of the samples is more realistic for practicing suturing and cutting, so it can be used to manufacture anatomical models of realistic soft tissue.

Study hypothesis

H1: It is expected that the new silicones will allow an improvement in the practice of suturing and cutting compared to the materials currently used, being more similar to live tissue.

H0: It is expected that the new silicones will not allow an improvement in the practice of suturing and cutting compared to the materials currently used, without being similar to live tissue.

Study design

The evaluation of the silicones will be carried out using two types of different samples.

The first type will consist of semi-spherical samples for practicing cutting, and the second type will consist of rectangular samples for practicing suturing. Each type of sample will consist of 3 specimens with different hardness and textures manufactured by IQS, together with 1 sample with silicone cast at the 3D4H unit for comparison.

The objective of the study will be measured through a qualitative study (Annex 1) based on previous publications to evaluate models intended for surgical planning [1]. A Likert scale will be used to assess statements on a scale from 1 to 5 (1. Strongly disagree, 2. Disagree, 3. Neither agree nor disagree, 4. Agree, 5. Strongly agree).

Sample size

It is expected that a minimum of 7 expert surgeons in the field will participate in the study to offer their opinion on the samples.

References

[1] Schlegel, L., Ho, M., Fields, J.M. et al. Standardizing evaluation of patient-specific 3D printed models in surgical planning: development of a cross-disciplinary survey tool for physician and trainee feedback. BMC Med Educ 22, 614 (2022). https://doi.org/10.1186/s12909-022-03581-7

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QUALITATIVE STUDY OF MATERIALS FOR SOFT TISSUE

Name: _____

Date: _____

Specimen/sample code: _____

Rate the following statements on a scale from 1 to 5 (1. Strongly disagree, 2. Disagree, 3. Neither agree nor disagree, 4. Agree, 5. Strongly agree).

FIDELITY

1. The tactile sensation of the tissue is realistic:

1	2	3	4	5

2. The tissue behaviour when cutting is realistic:

1	2	3	4	5

3. The behaviour in suture techniques is realistic:

1	2	3	4	5

UTILITY

4. The model is useful for educating students:

1	2	3	4	5

5. The material is useful for procedure Planning:

1	2	3	4	5

EXPERIENCE

6. The model was easy to use:

1	2	3	4	5

7. The model met the needs:

1	2	3	4	5

8. Would you use a specific 3D anatomical model for surgical practice with this material?

1	2	3	4	5

9. Regarding the similarity of the samples to human tissue:

- The tissue resembles kidney tissue:

1	2	3	4	5

- The tissue resembles brain tissue:

1	2	3	4	5

- The tissue resembles liver tissue:

1	2	3	4	5

- The tissue resembles pancreas tissue:

1	2	3	4	5

- The tissue resembles muscle tissue:

1	2	3	4	5

- The tissue resembles cartilage tissue:

1	2	3	4	5

- The tissue resembles adipose tissue:

1	2	3	4	5

- The tissue resembles skin tissue:

1	2	3	4	5

Specify which tissue/organ the behaviour of this sample resembles the most:

_____

Comments:

_____
_____
_____
_____
_____
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