In vivo estimation of skin elasticity: would you choose US Shear Wave Elastography or a custom-made aspiration device?

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1. Introduction

Sacral soft tissue (one of the common locations for pressure ulcer development) mechanical response to external loading could be estimated with Finite Element (FE) modelling. Tissue behaviour predicted by an FE model is highly dependent on the assumed constitutive parameters. *Ex vivo* experiments allow for controlled conditions (minimum variation in experimental models) but the identified parameters are non-personalized. Inter-individual variability can't be overlooked when dealing with patient-specific estimation of internal tissue loading. In the literature, three main approaches have been proposed for estimating constitutive parameters from *in vivo* experiments: indentation-based experiments, aspiration-based testing (Kappert et al. 2021) and using ultrasound shear wave elastography (US SWE) (Vergari et al. 2014).

The objective of the current study was to estimate the stiffness parameters of the sacral soft tissues using two techniques: an aspiration device and the US SWE.

2. Methods

2.1. Participants

Two healthy volunteers, a male (34 y.o., 1.75m, BMI 27.8 kg/m^2) and a female (30 y.o., 1.75m, BMI 20.9 kg/m^2), participated in the study. Before inclusion, the participants were informed of the purpose of the study and gave their consent to the experimental procedure.

2.2. Setups and measurement devices

Two measurement devices were used: a custom-built modified version of the aspiration device (Volume-based Light Aspiration device for *in vivo* Soft TIssue Characterization (VLASTIC) initially proposed by (Kappert et al. 2021)) and an Aixplorer US SWE device (Supersonic Imagine, Aix-en-Provence, France)

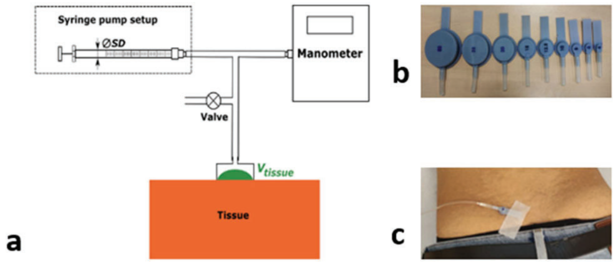

Figure 1. a) Scheme of the aspiration setup adapted from (Kappert et al. 2021). b) Nine cups of different diameters were used c) A cup positioned on the sacral region of subject 1.

with a 50 mm 18 MHz linear probe. A scheme of the aspiration device is shown in Figure 1. The principle is the following: A 3D printed semi-spherical cup is positioned on the skin surface and a negative pressure (1–50 mbar) is applied to the skin and underlying adipose tissues. A programmable syringe pump (pump 11 elite, Harvard Apparatus, Holliston USA) was used to remove an air volume from the system at a controlled rate (~8 seconds per cycle). Experiment was limited to small strains and acquisitions were performed with nine different cup diameters of 4, 6, 8, 10, 12.5, 15, 20, 25, and 30 mm. Cups of various diameters are indeed required to mechanically load soft tissues at different depths. All cups responses were used in order to solve the inverse problem.

2.3. Measurement protocols

Two healthy volunteers were instructed to lie prone in a comfortable position.

2.3.1. VLASTIC

Each cup was positioned on the upper left side from the medial sacral crest (Figure 1c) on the relatively flat surface. The region of interest (ROI) was marked for the further acquisitions. US gel was put on the edge of the cup to insure contact with the skin and to prevent pressure air leakage. Four cyclic pressurizations/depressurizations were applied for each acquisition. For both subjects, nine acquisitions with each of the cups were collected. Measurements were repeated three times to evaluate the uncertainties. Between acquisitions, the cup was taken off the skin, the excess gel was removed and the cup was repositioned once again at the same location.

2.3.2. SWE

A thick layer of US gel was put on the ROI to allow the measurements of the unloaded tissues; it was assumed that no pressure was applied by the US probe. The probe was held manually and positioned

Table 1. Young's moduli of the skin E_S and the adipose E_F tissues for two subjects (S_1 and S_2) for three evaluations with VLASTIC and SWE.

		VLASTIC		SWE	
S	#	E_S kPa	E_F kPa	E_S kPa	E_F kPa
S_1	1	35.1	1.9	17.9	11.0
	2	40.7	1.8	18.4	10.8
	3	37.2	1.8	16.3	8.7
S_2	1	41.3	0.4	13.2	11.3
	2	40.0	0.6	14.3	9.1
	3	41.6	0.5	17.6	10.2

perpendicular to the spine at approximately 90 degrees to the skin surface. Three series of 10 continuous images were recorded with the US device set to 'general mode', 'low' spatial smoothing and 3-image temporal smoothing for each subject for the ROI including the skin and underlying tissues according to the protocol defined in (Dubois et al. 2015). The rectangular ROI was selected for each image to include as much of the tissue as possible. At the end, an additional image of the undeformed tissues in B-mode was taken to measure the thickness of the skin.

2.4. Post-processing

2.4. Post-processing VLASTIC

A bi-layer structure of the soft tissues was assumed, with a non-linear elastic Neo-Hookean model constitutive law for both the skin and the underlying fat tissues. The stiffening behaviour of the tissues was not considered in the current study. The reader is referred to (Kappert et al. 2021) for more details.

An inverse FE-based procedure was employed to identify the initial constitutive parameters. The optimization cost function was defined as a least square of the offset between the numerical and experimental results. Thickness of the top layer (skin) of the FE model was imposed based on the pre-measured values from the US B-mode images. Linearized Young's moduli of the skin and the adipose tissue (respectively, E_s and E_F) were identified from the 36 pressure-volume experimental curves (4 cycles $\times$9 cup size).

2.4. Post-processing SWE

Images were extracted from the SWE videos and processed using a custom-made MATLAB code (Vergari et al. 2014). Young's moduli for skin and adipose tissues obtained from three videos were averaged.

3. Results and discussion

The resultant Young's moduli estimated for both layers are provided in Table 1 for VLASTIC (with the pre-measured skin thickness of 2.9 mm and 3.0 mm for subjects 1 and 2, respectively) and SWE measurements.

Average (E_S, E_F) values assessed with VLASTIC for S_1 and S_2 were (38 kPa, 2 kPa) and (41 kPa, 0.5 kPa) correspondingly, while the values assessed with SWE were (18 kPa, 10 kPa) and (15 kPa, 10 kPa).

There are some limitations to the methods used to derive the stiffness values from the aspiration acquisitions and SWE: both materials (skin and adipose tissues) are considered to be homogeneous isotropic and linear-elastic (only initial slope of the curve was assessed). In addition, when it comes to the results of SWE, Young's modulus is not measured directly, it is derived from the measured wave velocity. While, according to the previous research, the shear wave propagation is highly dependent on the US probe positioning, tissue fibre direction and pre-strain. Another limitation is the fact that only two volunteers participated in this study.

4. Conclusions

Currently, there is no fully validated method for *in vivo* estimation of human soft tissue elasticity. This study has tested whether the Young's moduli for the skin and the adipose tissue derived from the VLASTIC aspiration measurements and by SWE would be similar. Young's modulus values obtained with the aspiration device seem more consistent with the literature (see for example the study of Pailler-Mattei et al. deriving the elastic parameters for the forearm tissues with Young's modulus of the dermis to be 35 kPa and shear modulus of the hypodermis to be 2 kPa (Pailler-Mattei, Bec, and Zahouani 2008)). On the contrary, this study suggests that values directly obtained with SWE should be used with caution, in particular when the distinction between skin and hypodermis tissue is targeted. However, further work is needed to validate the results obtained with VLASTIC.

Disclosure statement

No potential conflict of interest was reported by the authors.

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