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Reliability of B-mode Ultrasound and shear wave elastography in evaluating sacral bone and soft tissue characteristics in young adults with clinical feasibility in elderly

Maher Abou Karam ^a , Ekaterina Mukhina ^b , Nils Daras ^a , Isabelle Rivals^{c, d} ,
Helene Pillet ^a , Wafa Skalli ^a , Nathanaël Connesson ^b , Yohan Payan ^b , Pierre-Yves
Rohan ^{a, *}

^a Institut de Biomécanique Humaine Georges Charpak, Arts et Métiers ParisTech, 151 bd de l'Hôpital, 75013 Paris, France

^b Univ. Grenoble Alpes, CNRS, Grenoble INP, TIMC-IMAG, Grenoble, France

^c Sorbonne Université, INSERM, UMRS1158 Neurophysiologie Respiratoire Expérimentale et Clinique, Paris, France

^d Equipe de Statistique Appliquée, ESPCI Paris, PSL Research University, Paris, France

Keywords: pressure ulcer, sacrum, medial sacral crest, elderly, ultrasound, shear wave elastography, elasticity, reliability

List of abbreviations:

B-mode, Brightness mode; CI, confidence interval; CT, Computed tomography; FE, Finite element; HT, Hypodermis thickness; hSWE, hypodermis shear wave elastography; HE, Medial sacral crest height; ICC, intraclass correlation coefficient; IT, ischial tuberosity; MRI, Magnetic resonance imaging; MSC, Medial sacral crest; mSWE, muscle shear wave elastography; OA, Medial sacral crest opening angle; PSIS, Posterior superior iliac spine; PU, Pressure ulcer; ROC, Medial sacral crest radius of curvature; ST, Skin thickness; SWE, Shear wave elastography; sSWE, Skin shear wave elastography; US, ultrasound.

Highlights

- In the elderly loss of mobility, sarcopenia, skin atrophy, and loss of elasticity contribute to the occurrence of a pressure ulcer (PU)
- Bedside B-mode US and SWE protocol was proposed to evaluate skin, hypodermis, and muscle morphology and mechanical properties
- The protocol was tested for reliability on 19 healthy young subjects, and clinical feasibility on 11 healthy older people
- Reliability was mostly unsatisfactory despite efforts to standardize protocol and measurement definitions
- Perspective work will review protocol to increase reliability and evaluate risk in elderly in nursing homes

Abstract

Background: Physiologic aging is associated with loss of mobility, sarcopenia, skin atrophy and loss of elasticity. These factors contribute, in the elderly, to the occurrence of a **pressure ulcer (PU)**. Brightness mode ultrasound (US) and **shear wave elastography (SWE)** have been proposed as a patient-specific, bedside, and predictive tool for PU. However, reliability and clinical feasibility in application to the sacral region have not been clearly established.

Method: The current study aimed to propose a simple bedside protocol combining US and SWE. The protocol was first tested on a group of 19 healthy young subjects by two operators. The measurements were repeated three times. Eight parameters were evaluated at the medial sacral crest. Intraclass Correlation Coefficient (ICC) was used for reliability assessment and the modified Bland Altman plot analysis for agreement assessment. The protocol was then evaluated for clinical feasibility on a healthy older group of 11 subjects with a mean age of 65 ± 2.4 yrs.

Findings: ICC showed poor to good reliability except for skin SWE and hypodermis thickness with an ICC (reported as: mean(95%CI)) of 0.78(0.50-0.91) and 0.98(0.95-0.99) respectively. No significant differences were observed

between the young and older group except for the muscle Shear Wave Speed (SWS) (respectively 2.11 ± 0.27 m/s vs 1.70 ± 0.17 m/s).

Interpretation: This is the first protocol combining US and SWE that can be proposed on a large scale in nursing homes. Reliability, however, was unsatisfactory for most parameters despite efforts to standardize the protocol and measurement definitions. Further studies are needed to improve reliability.

Introduction

Tissue morphology, mechanical properties, physiology, and repair properties can all change over time as a result of aging, lifestyle, chronic injury, or disease. Over a bony prominence, these changes - associated with a mechanical load - can lead to a localized injury known as a “pressure ulcer” [1].

The prevalence of this lesion ranges between 9% [2] and 15% [3] in long term care or hospitalized patients , and is most frequently observed over the sacrum or the heel. Two thirds of PU are observed in patients above 70 years of age [4]. The occurrence of PU is associated with significant increase in hospital costs, length of stay and, most importantly, an increased risk of death. [5]–[7].

While numerous and efficient therapies have been developed, prevention remains the center of interest of all healthcare professionals and thus of researchers [4]. However, current practices in PU prevention are far from satisfactory with more than 85% lack in documented repositioning care plan. This is majorly due to the lack of staff and time [2]. PU prevention protocols are based on risk assessment tools or scales (Norton scale, Braden scale...) [8]. The impact of these tools on the incidence of PU remains uncertain and fail to meet the needs of all patients in different clinical settings [7].

The process of aging is associated with physiological changes including sarcopenia, osteoporosis, progressive increase in blood glucose and skin atrophy [9]. The decrease in muscular power has a high impact on the performance of daily activities even in healthy older persons leading to increased immobility [10]. In consequence, the elderly are considered at risk of developing PU and therefore, a target group for preventive screening protocols. Several bedside technologies combined with assessment tools were investigated for early detection of PU, especially in long term care

facilities. High frequency ultrasound (HFUS) was particularly studied, given its accessibility and capacity to detect preclinical superficial skin changes, mainly the presence of fluid/oedema at different levels of the skin [11]. However, a randomized controlled trial [12] failed to demonstrate that HFUS was an effective strategy for predicting the development of Category/Stage I PUs of the heel or sacrum compared with a focused physical assessment. Also, a systematic review [13] evaluated HFUS among other technologies. Despite giving meaningful and consistent results, it could not be recommended due to lack of reliability of protocols, being limited to detecting macroscopic level tissue damage, and its training requirements for image interpretation.

In terms of etiology/pathophysiology, studies based on both *in vitro* (cell models) and *in vivo* (animal models) approaches have demonstrated that at least two damage mechanisms, are involved in the development of PU: first, compression damage due to tissue ischemia/reperfusion initiated by local, moderate and persistent mechanical loads; secondly, direct deformation damage above a threshold level related to shear strain; even for a short period of time (during transfer from bed to a wheelchair for example) [14]. These results suggest the presence of a direct link between mechanical determinants and biological processes leading to tissue damaging and, in fine, necrosis.

Based on the rationale that elucidating the relationship between external loads and internal local stresses and strains within loaded soft tissues has the potential of improving the management and prevention of PUs, several Finite Element (FE) models of the buttocks have been proposed in the literature. Models are mostly based on the segmentation of MRI or CT scan sequences [15]–[18]. However, the use of MRI and CT scans is limited due to cost, accessibility, and time [19]. In this perspective, brightness mode (B-mode) ultrasound (US) imaging was proposed as an alternative to MRI or CT-scan. Feasibility, reproducibility, and its use for personalized FE models were investigated mainly over the ischial tuberosity [19]–[23].

Recent studies [19], [24], [25] proposed B-mode US for the evaluation of biomechanical risk of PU in a seated position by assessing, among other parameters, tissue thickness changes in different positions. On the other hand, ultrasound elastography, a relatively new method that shows structural changes in tissues following application of physical stress can be used in the examinations of musculoskeletal system [26]. Shear wave elastography (SWE) uses focused ultrasonic beams, to remotely generate mechanical vibration sources radiating low-frequency, shear waves inside tissues [27]. It allows a bedside evaluation of the local mechanical properties of soft biological tissues by assessing shear modulus [28]–[30]. Experiments demonstrated that ultrasound elastography is a promising technique for PU detection, especially at an early stage of the pathology, when the disease is still visually undetectable [28].

Previous studies investigating the combination of B-mode US and SWE elastography in the context of PU prevention focused on potential changes of tissue stiffness during prolonged loading [31] or tissue characteristics in different body postures [32].

The current study aimed to propose and test a bedside B-mode US and SWE protocol that can be used as a risk assessment tool for sacral PU in elderly. The protocol was designed for the evaluation of bone geometry, tissue morphology and mechanical characteristics over the sacrum. Reliability and reproducibility of our protocol were tested on a healthy young adults group. The protocol was then applied on a group of healthy older people to assess for clinical feasibility.

Materials and methods

1. Data Collection

The current study was approved by the ethics committee (Comité de protection des Personnes CPP NX06036) and each subject gave an informed consent. For the reproducibility analysis 19 young healthy subjects participated to the experiment, 8 women and 11 men (Age: 25.7 ± 3.8 yrs, Weight: 75.2 ± 16.4 kg, BMI: 24.5 ± 4.9 kg/m²). For the elderly group 11 healthy subjects, 7 women and 4 men were recruited (Age: 65 ± 2.4 yrs, Weight: 72.5 ± 18.6 kg, BMI: 25.34 ± 5 kg/m²). Exclusion criteria included: the presence of chronic or acute low back pain, history of lower spine surgery or sacral PU, and the presence of PU skin signs at the moment of the acquisition.

Ultrasound acquisition protocol

B-mode US images and shear wave elastography (SWE) videos were obtained using a commercial device (SupersonicMach30, SuperSonic Imagine, France). Two probes were used, the curvilinear (SuperCurved C6-1X) with low frequency (1 to 6 MHz allowing increased depth visualization) and large field of view, and the linear (SuperLinear L10-2) probe with a higher frequency (2 to 10 MHz allowing superficial layers visualization). The general mode and penetration optimization were chosen for all acquisitions.

A standardized - tissue and musculoskeletal US/SWE over the sacral region - protocol was developed and was first pilot tested on a sample of three healthy young volunteers, consequently, adjustments were made. The definitive protocol is described thoroughly in Appendix 1.

Acquisitions were taken in the lying prone position. After anatomic palpation of the two posterior superior iliac spines (PSIS), the curvilinear probe was first used in B-mode to recognize the anatomic region of interest: the MSC. An image was captured to assess bone anatomy and the skin was marked with a tape. Switching to the linear probe, the second image captured the skin and hypodermis at the level of the MSC. The third part, also using the linear probe at the marked skin level, was a series of three videos (of 10 seconds each) in SWE mode with a region of interest (ROI) including both skin and hypodermis. For the fourth and last part, three SWE videos of the gluteus maximus muscle were taken lateral to the sacro-coccygeal region at the lower part of the sacrum. The images/videos using the linear probe were taken with minimal applied pressure, using a thick gel layer and making sure it was visible on the US image. A summary of the acquisition protocol and images are shown in figure 1.

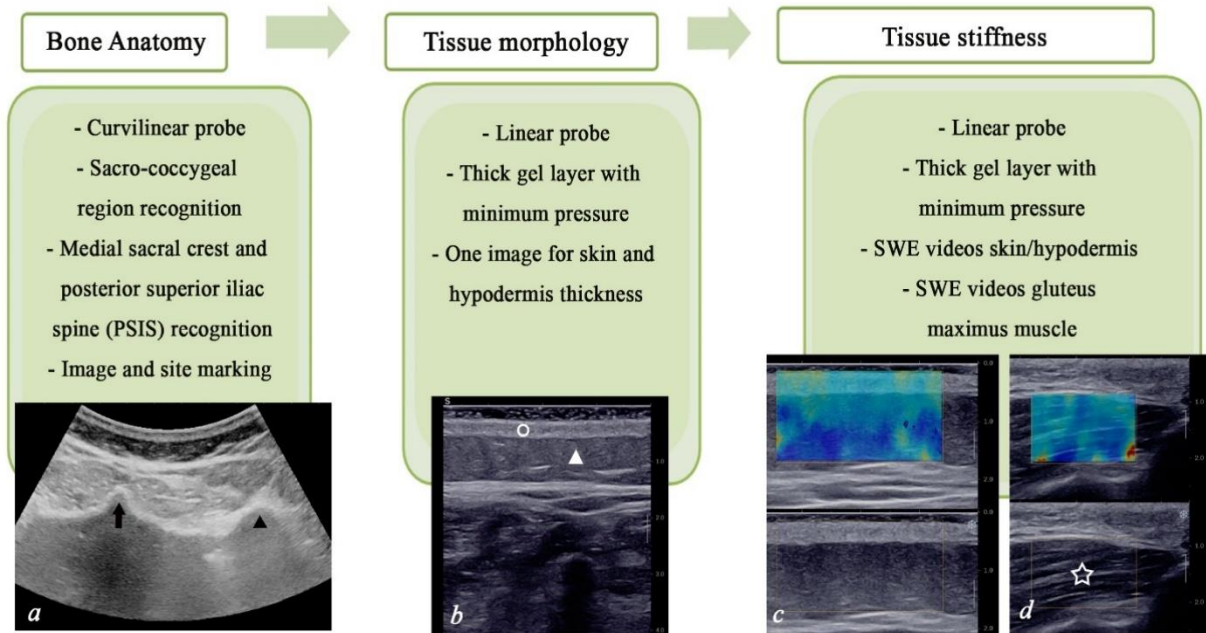


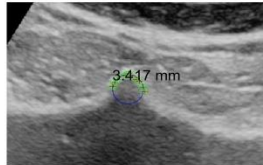
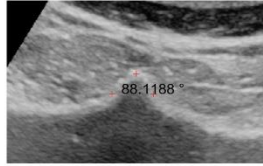

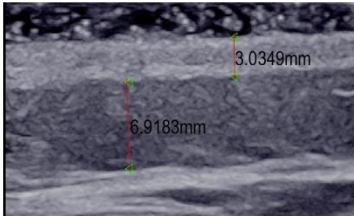
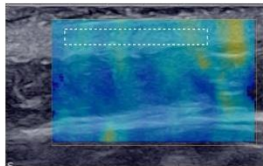
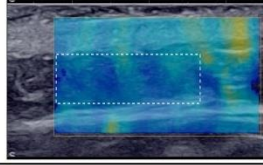
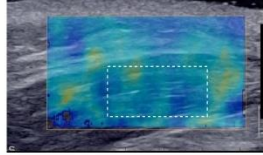
Fig. 1. US acquisition protocol of the sacral region in the transverse view. In B-mode: the medial sacral crest (arrow) at the level of the PSIS (black triangle) (a), skin (circle) and adipose tissue (white triangle) over MSC (b); in SWE mode: the skin and adipose tissue (c), gluteus maximus muscle (star) (d).

Parameter estimation

To reduce acquisition time, processing and measurements for images/videos were done separately using a custom

139 software written in Matlab (R2019a) (MathWorks, Inc, Natick MA). In total 8 parameters were measured using the
140 images/videos captured during each acquisition. First, the bone anatomy image (fig.1a) was used to measure the MSC
141 radius of curvature (ROC), opening angle (OA), and height (HE). Then, the second image (fig.1b) was used to measure
142 the skin thickness (ST) and the hypodermis thickness (HT). For the SWE videos of the third (fig.1c) and fourth (fig.1d)
143 part of the acquisition, images were extracted and processed using a separate written code [33]. The average value of
144 the images of each video was calculated and then, the average of the three videos determined the shear wave velocity
145 of one acquisition for: the skin (sSWE), the hypodermis (hSWE), and gluteus maximus muscle (mSWE). Details about
146 the definitions and recommendations for these measurements are reported in table 1.

Table 1. Description of parameter measurement post acquisition using a customized MATLAB algorithm

	Parameter name	Description	Post-processing
<i>Bone anatomy (curvilinear probe - B-mode)</i>	Radius of curvature (ROC)	10 points distributed equally on both sides of the tip of MSC ; the circle plotted was viewed to ensure it captures the shape of the tip (19)	
	Opening angle (OA)	3 points: one on the middle of the MSC tip and two bilateral points	
	Height (HE)	3 points: the geometry of the MSC could be compared to a triangle, the tip is the highest point of the triangle and two points for the base of the MSC; the distance from the upper point to the base is the HE	
<i>Tissue morphology (linear probe - B-mode)</i>	Skin thickness (ST)	2 points: the upper limit marked by the most superficial, homogenous, and continuous line of the epidermis; lower border marked by the transition between dermis and hypoechoic adipose tissue	
	Hypodermis thickness (HT)	2 points: thickest hypoechoic region under the skin; hyperechoic muscle fascia marks the lower border	
<i>Tissue stiffness (linear probe – SWE mode)</i>	SWE hypodermis (hSWE)	Region of interest (ROI): largest, most homogenous SWE signal	
	SWE skin (sSWE)		
	SWE gluteus muscle (mSWE)		

2. Method Evaluation

Sample size and Reliability assessment

All the data were analyzed with the IBM SPSS for Windows (Version 27.0. Armonk, NY: IBM Corp).

The reliability study was conducted on the young, healthy group by two operators: a physician and an engineer. Both operators received extensive training consisting of two phases: first, measurements were repeated until reaching adequate reproducibility compared with an expert sonographer then, deviations were assessed, and possible problems were determined and corrected.

The operators were asked to repeat the protocol three times on each subject, i.e., captured three images for each of the bone geometry parameters and tissue morphology, and nine SWE videos for each tissue stiffness parameter.

The reliability of our protocol was assessed by calculating the intra class correlation coefficient (ICC) for within-operator and between-operator for the young subjects group [34]. The minimum sample size required for this test-retest reliability study was estimated based on the recommendations made in Bujang et al [35]. With three observations per subject, a minimum sample size of 15 is required to detect an ICC value of 0.5 with power of 90% when taking a type I error risk of 5% (table 1a of [35]).

Given that ultrasound acquisition is highly operator dependent, and that the processing/measurement of a given image/video (i.e. definitions of parameters) might also differ from one operator to another, we decided to quantify the variability first at processing level, and then at both processing and acquisition level. First, the two operators processed and measured one acquisition conducted by the physician on all subjects. Each operator repeated measurement of the same image/video three times, allowing an intra-image analysis [36]. For this analysis, the ICC model 3 (2-way mixed) was chosen for within-operator reliability, and ICC model 2 (2-way random) for between-operator reliability with absolute agreement type and single measure [37]. For between operator reliability, values of one of the three measurement, chosen randomly for each operator, was used. Then, each operator processed and measured their own acquisitions allowing an inter-image analysis [36]. The same model and type for within-operator ICC (2-way mixed and absolute agreement) were used with single measure, and for between-operator reliability also the ICC model 2 was used but with consistency agreement type and single measure since different images are compared. Also, for between operator reliability, values of one of the three measurements, chosen randomly for each operator, was used. This procedure was conducted for each parameter and the ICC with 95% confidence interval was reported. Values less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.90 indicated poor, moderate, good, and

excellent reliability, respectively [37].

Agreement assessment

The modified Bland Altman plot analysis for continuous measures [38] was used as a measure of the level of agreement within and between operators for both the intra-image and inter-image analysis. **In the absence of a gold standard, the value of each measurement was compared to the average of all measurements for one subject (bias line equal to zero).** The difference between each observer and the overall mean for a subject is estimated. The 95% level of agreement with the mean is estimated as $\pm 2 \times$ Standard deviation (SD), where SD represents the square root of the variance of the differences.

Healthy young adults vs healthy elderly

The same protocol was conducted once (one acquisition and measured once) on the older group by one operator: the physician. For the young adults group data, the measurements of one of the three acquisitions collected by the physician were chosen randomly. **Normality was checked with the Shapiro–Wilk test and the equality of variance was assessed with the Levene's test. If both normal distribution and equality of variance of the different groups could be assumed, data were reported per parameter and per group as mean ± 1 SD and groups (young versus old) were compared using the student t-test. In case the normality or equality of variance assumption was violated, groups were compared with the Wilcoxon test. For all the tests, the significance level was set at 0.05 *a priori*.**

Results

Reliability assessment

Within operator and between operator ICC with the 95% confidence interval, for both the intra and inter-image analysis for all parameters, are reported in table 2. First in the intra-image analysis, all ICC confidence interval values showed good to excellent reliability for within operator, except for the ROC, and the OA of the MSC for the physician with moderate to excellent reliability. For between operator ICC the following parameters: HE, hypodermis thickness, SWE skin, SWE hypodermis, SWE muscle, showed good to excellent reliability. The ICC for the OA and the skin thickness showed moderate to excellent reliability. For the inter-image analysis, within operator ICC showed excellent reliability for the hypodermis thickness parameter for both operators. The physician (operator 1) showed good to excellent

reliability for the ROC and HE. For the SWE skin parameter he showed moderate to excellent reliability; for the opening angle parameter moderate to good reliability; for the remaining parameters poor to good reliability. The engineer (operator 2) showed moderate to excellent reliability for the ROC, SWE skin, SWE hypodermis, and SWE muscle parameters. For the opening angle parameter, the engineer showed moderate to good reliability; for the HE, skin thickness poor to good reliability. The between operator ICC also showed excellent reliability for the hypodermis thickness. The ICC for SWE skin parameter showed moderate to excellent reliability. The ICC of the remaining parameters showed poor to good reliability.

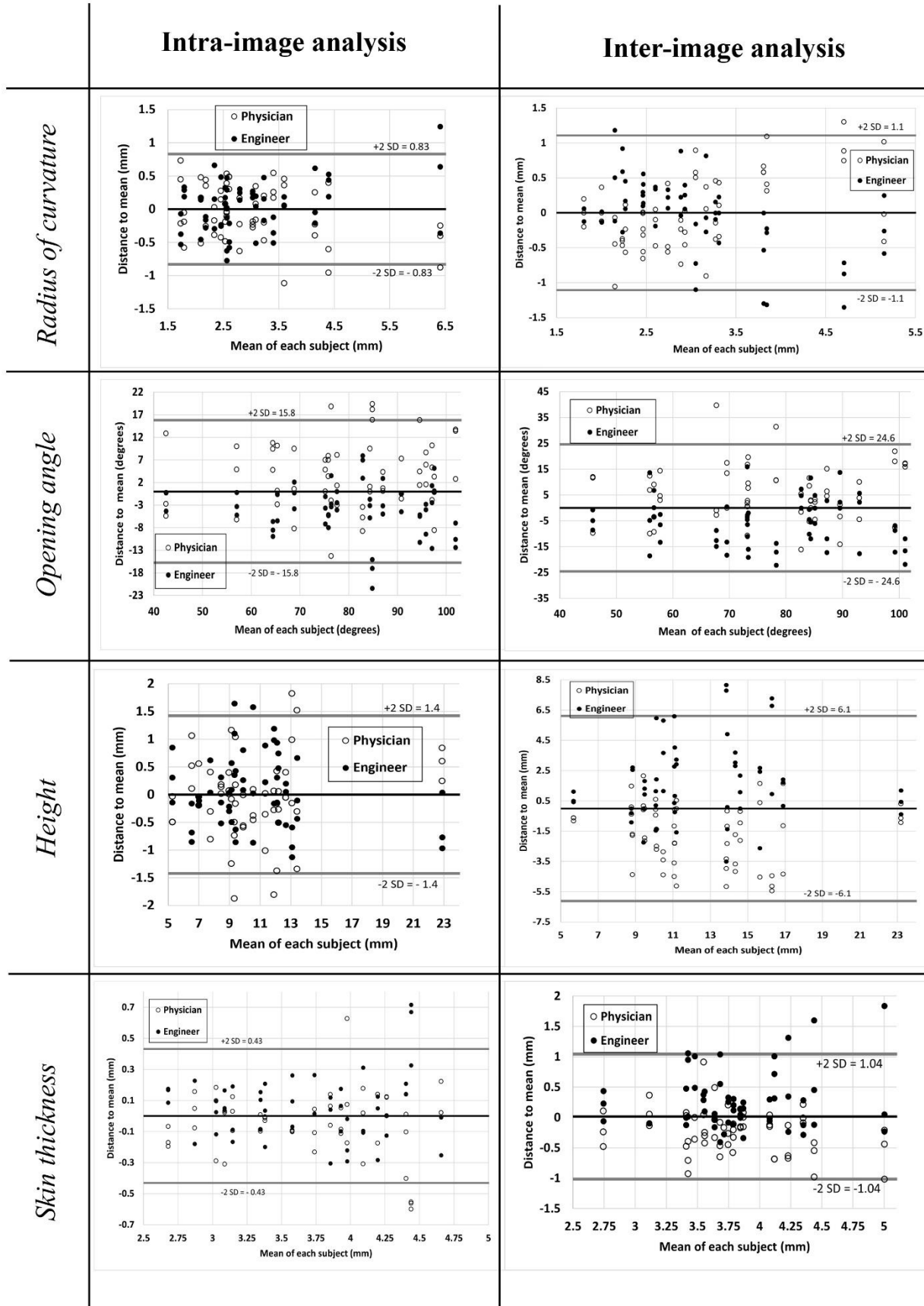
Table 2. Reliability assessment results with Intraclass correlation coefficient ICC for both intra-image and inter-image analysis for both operators: 1 the physician and 2 the engineer.

Parameter	Operator	Intra-image analysis		Inter-image analysis	
		Within operator ICC (95% CI)	Between operator ICC (95% CI)	Within operator ICC (95% CI)	Between operator ICC (95% CI)
Radius of curvature	1	0.86(0.68-0.94)	0.84(0.64-0.94)	0.90(0.79-0.96)	0.69(0.34-0.87)
	2	0.93(0.84-0.97)		0.76(0.53-0.90)	
Opening angle	1	0.86(0.66-0.94)	0.81(0.57-0.92)	0.74(0.53-0.89)	0.58(0.17-0.82)
	2	0.96(0.91-0.98)		0.73(0.50-0.88)	
Height	1	0.97(0.93-0.99)	0.97(0.92-0.99)	0.89(0.78-0.96)	0.74(0.43-0.89)
	2	0.98(0.95-0.99)		0.69(0.45-0.87)	
Skin thickness	1	0.94(0.87-0.97)	0.88(0.73-0.95)	0.71(0.49-0.87)	0.53(0.09-0.80)
	2	0.95(0.88-0.98)		0.59(0.32-0.80)	
Hypodermis thickness	1	0.99(0.99-1.00)	0.99(0.99-1.00)	0.98(0.96-0.99)	0.98(0.95-0.99)
	2	0.99(0.99-1.00)		0.99(0.98-1.00)	
SWE skin	1	0.99(0.99-1.00)	0.99(0.99-1.00)	0.83(0.67-0.93)	0.78(0.50-0.91)
	2	0.99(0.99-1.00)		0.85(0.72-0.94)	
SWE hypodermis	1	0.99(0.98-1.00)	0.98(0.94-0.99)	0.70(0.46-0.86)	0.65(0.27-0.85)
	2	0.98(0.97-0.99)		0.80(0.63-0.91)	
SWE muscle	1	0.96(0.88-0.99)	0.93(0.79-0.98)	0.71(0.41-0.90)	0.41(-0.22-0.80)
	2	0.98(0.96-1.00)		0.84(0.63-0.95)	

214
215

216 *Agreement assessment*

217 The modified Bland Altman agreement plots for both the intra and inter image analysis are reported in figure 2. The
218 95% limits of agreement with the mean varied from the intra to the inter-image analysis as follows: for the ROC from
219 ± 0.83 mm to ± 1.1 mm; for the opening angle from ± 15.8 degrees to ± 24.8 degrees; for the HE from ± 1.4 mm to ± 6.1
220 mm; for the skin thickness from ± 0.43 mm to ± 1.04 mm; for the hypodermis thickness from 0.57 mm to 1.4 mm; for
221 the SWE skin from ± 0.03 m/s to ± 0.33 m/s; for the SWE hypodermis from ± 0.06 m/s to ± 0.29 m/s; and for the SWE
222 muscle from ± 0.08 m/s to ± 0.25 m/s.



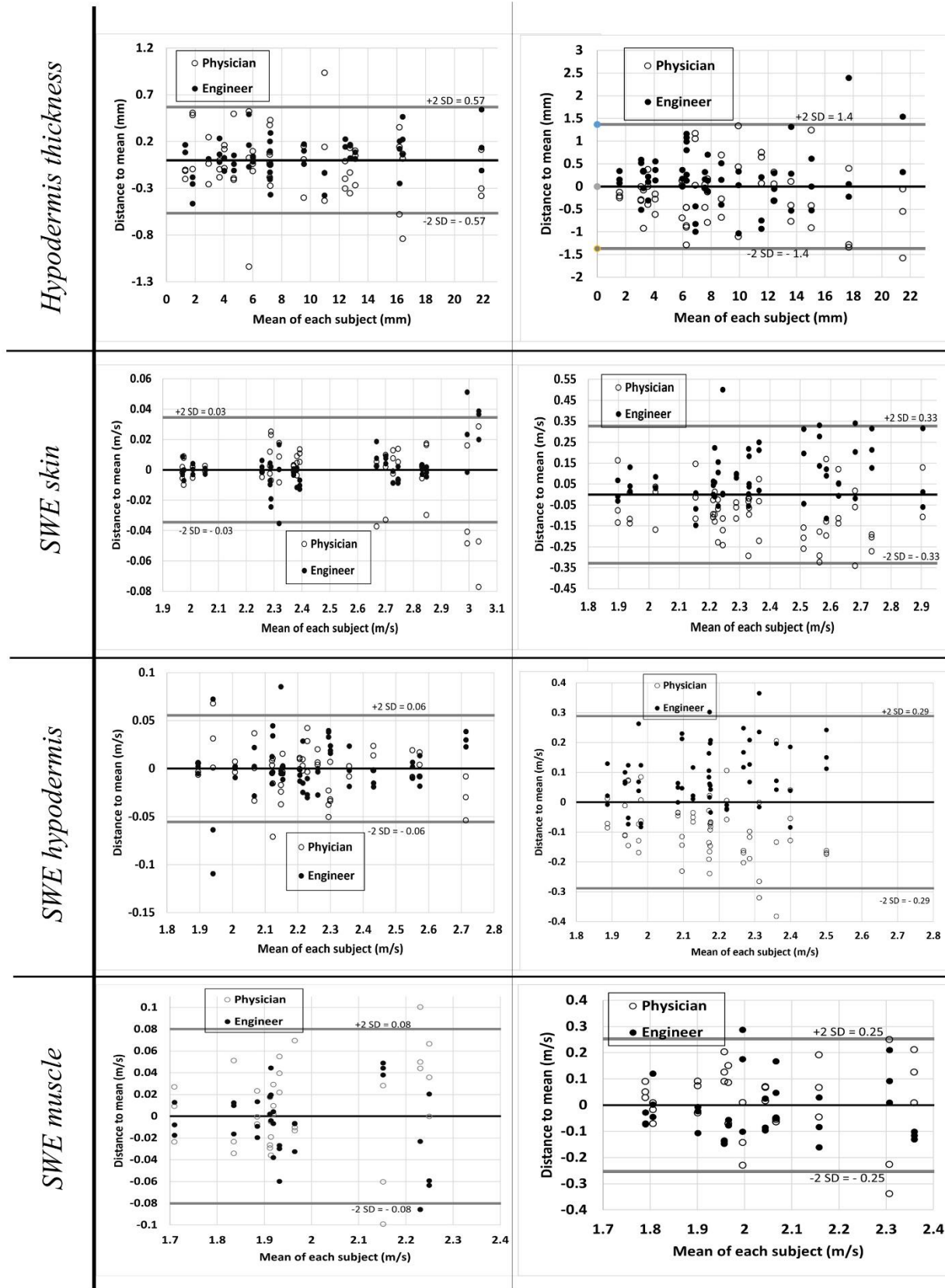


Fig. 2. Agreement plots with the mean of measurements for the intra-image and inter-image analyses for the 8 parameters

Healthy Young adults VS healthy elderly

The results of means, normality tests and Student's t-test test are reported in table 3. There was insufficient evidence to claim that the distributions were not normal or that the variances were not equal. Based on the results of the student T-test, we concluded that there is a statistically significant difference only for the SWE of the muscle (2.11 ± 0.27 m/s for the young adults group vs 1.70 ± 0.17 m/s for the elderly, p-value = 0.001). Because of the relatively small sample size, the sample means for each parameter were also compared with the Wilcoxon signed rank test. The conclusions were the same i.e. there is a statistically significant difference only for the SWE of the muscle.

Images reported in figure 2 show observations for the older group subjects that diverged from the group. The upper and lower limits for skin and hypodermis SWE were found in a 62-year-old male subject with a BMI of 39.1 kg/m^2 (fig.2a) and a 67-year-old male with a BMI of 27.4 kg/m^2 (fig.2b), respectively. A 62-year-old female elderly with a BMI of 22.3 kg/m^2 (fig.2c) showed a heterogeneous distribution of hypodermis thickness over the MSC.

Table 3. Mean of each parameter for the young adults group and healthy elderly, normality using Shapiro-wilk test and comparison using Student's t-test.

Parameter		Young adults		Healthy elderly		Student's t-test p-value
		Mean \pm SD	Shapiro Wilk test p-value	Mean \pm SD	Shapiro Wilk test p-value	
Bone anatomy (MSC)	OA (°)	80.32 ± 21.06	0.628	79.54 ± 19.19	0.509	0.920
	HE (mm)	10.39 ± 4.45	0.119	8.20 ± 2.94	0.293	0.159
	ROC (mm)	2.90 ± 1.21	0.191	2.19 ± 0.17	0.550	0.088
Tissue morphology	ST (mm)	3.61 ± 0.55	0.982	3.30 ± 0.53	0.215	0.147
	HT (mm)	8.67 ± 5.21	0.380	6.08 ± 3.56	0.457	0.156
Tissue stiffness	sSWE (m/s)	2.27 ± 0.28	0.087	2.22 ± 0.55	0.295	0.800
	hSWE (m/s)	2.06 ± 0.16	0.497	1.98 ± 0.33	0.437	0.465
	mSWE (m/s)	2.11 ± 0.27	0.128	1.70 ± 0.17	0.758	0.001

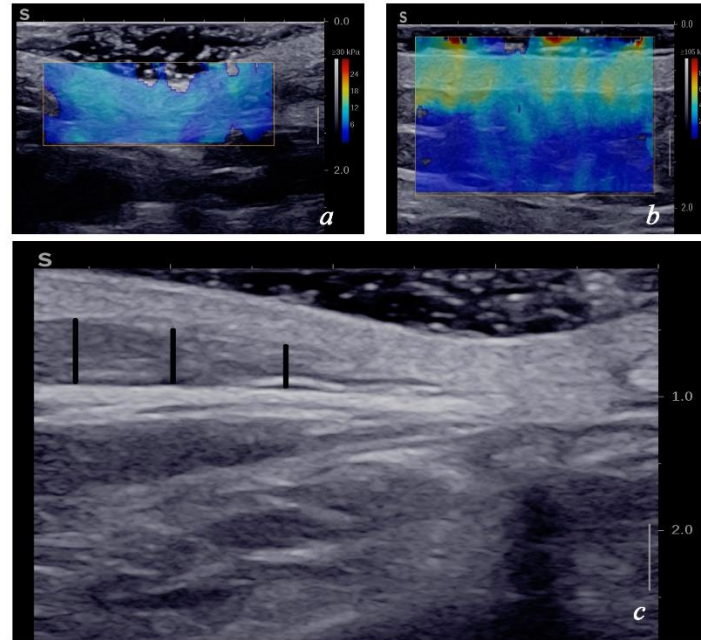


Fig. 3. Observations in the elderly group: lowest and highest skin/hypodermis SWE signal (a,b respectively), hypodermis heterogeneous thickness distribution over the MSC (black vertical lines) (c)

Discussion

This study aimed to evaluate the use of B-mode US and SWE in the assessment of bone geometry, tissue morphology and tissue stiffness in the context of sacral PU prevention in elderly. A protocol was developed to evaluate the region over the MSC. It was tested for reliability on a group of 19 healthy young subjects by two operators: a physician and an engineer. Afterwards, the protocol was tested on a group of 11 healthy older people by the physician only. The parameters evaluated by our protocol were: the radius of curvature (ROC), opening angle (OA), and height (HE) of the MSC for the bone geometry; the skin thickness (ST), and hypodermis thickness (HT) for the tissue morphology; skin shear wave velocity (sSWE), hypodermis shear wave velocity (hSWE), and muscle shear wave velocity (mSWE) for tissue stiffness.

1. Reliability study

The intra-image analysis was first conducted to assess the operators understanding and reliability of measuring each parameter. Within-operator ICC was good to excellent for all parameters for the engineer. For the physician, most parameters showed good to excellent reliability except for the ROC (CI 0.68-0.94) and OA (CI 0.66-0.94), showing moderate to excellent reliability. This might be due to an unclear definition of these two parameters. While the ROC is measured by placing points on the tip of MSC, the position of the start and ending points are not always clear. Between operator ICC, for the intra-image analysis, showed good to excellent reliability for all parameters except ROC, OA, ST with moderate to excellent reliability. These results also highlight the difficulty in choosing the points for the ROC and OA. For the ST parameter, although the skin is a continuous layer over the hypodermis, both stratum corneum : the most superficial layer of the epidermis, and the reticular layer: the lower part of the dermis, are wavy layers and thus might affect ST measurement depending on the part of the image chosen to assess ST [39]. The inter-image analysis aimed to test whether operators are capable of successfully repeating an acquisition three times and reproducing the acquisition protocol. Because acquisitions measured were not the same, ICC results were expected to have lower values. The discussion will involve only the parameters that showed good to excellent reliability on the intra-image analysis. First the HE parameter, within operator reliability was good to excellent for the physician but low to good for the engineer. A possible explanation might be that the acquisitions were not taken at the same level over the MSC. Another explanation is the fact that, in terms of anatomy, the sacrum is the most variable portion of the spine. In fact, the MSC is formed by the fusion of the spinous processes of the first three to four sacral vertebrae, and therefore bone morphology might differ from a level to another [40]. In this perspective, an emphasis should be on taking the acquisition at the level of the two PSIS, since it is a fixed, palpable and US visible anatomic landmark (using the curvilinear probe). Also, the only study, that the authors found in the literature, that included US and SWE tissue evaluation of the sacral region reported neither the protocol of measurement nor the US anatomic landmark used during acquisition [31]. The authors think that this biased the results since the anatomy of the sacrum is complex and irregular [40], [41].

For the shear wave velocity: within operator and between operator ICCs showed moderate to excellent reliability for the skin; low to good reliability for hypodermis and muscle for both within and between operator ICCs. Possible reasons include signal instability and inhomogeneity associated with tissue depth and operator's experience. Another reason might be tissue anisotropy, therefore tissue SWE signal depends on the orientation of the probe relative to the layer tested. Also, this affects much more muscular fibres since they're organised with a geometric alignment

compared with the less structured adipose tissue or skin [42]. This explains the larger gap observed in the CI of between operator ICC for the mSWE (table 2).

The agreement plots were drawn to assess clinical significance of difference between measurements even when a parameter showed good reliability [38]. In the absence of a gold standard imaging tool in our study the level of agreement necessary for confident usage remains uncertain. However, we hypothesized that the clinical difference between different groups is significantly higher than the uncertainty of the measurements. For the bone geometry parameters, previous studies focused on ischium morphology and its impact on internal soft tissue strain thus on the occurrence of PU using mainly FE models [23], [43]. Our aim was to combine the three bone parameters : ROC, OA, and HE to differentiate a sharp tip from a flat tip [44]. For our knowledge, no research was conducted on the impact of the shape of the MSC on surrounding tissue deformation. In fact, reliability of bone morphology assessment using ultrasound is controversial: [19] found good between operator reliability for ischial tuberosity (IT) radius of curvature but they only reported the average ICC = 0.712 , while [20] found poor reliability for estimating inferior curvature of the IT in both its short and long axis. The methodology for our protocol combining an intra-image and-inter image analysis seemed promising but, with lack of reliability in the results and no clinical baseline for the MSC morphology, no interpretation could be given to the agreement plots reported in figure 2 for these parameters.

For tissue morphology parameters, skin thickness showed low reliability and a 95% CI of agreement with the mean of $\pm 1.04\text{mm}$ for the inter-image analysis. With a maximum skin thickness reported in the literature of 4mm [39] this parameter needs further investigation before clinical use. A possible solution might be to tell operators to measure the ST directly over the MSC. In this perspective and since the linear probe is limited in depth and field of view, the first acquisition using the curvilinear probe is crucial for identifying and marking the level of the MSC, but also its exact position over the spine midline. In fact, previous studies investigating the inter-operator reliability of tissue thickness measurement over IT showed : excellent reliability for total thickness with an average ICC=0.948, also without reporting the confidence interval [19] ; moderate to excellent reliability (0.60-0.95) for skin and fat thickness [20]. To our knowledge, no study investigated the reliability of measuring tissue thickness using US over the sacrum. On the other hand, hypodermis thickness parameter showed excellent reliability and a 95% CI of agreement with the mean of $\pm 1.4\text{mm}$ for the inter-image analysis. Since hypodermis thickness is variable, and mainly related to body mass index [45] with a value exceeding sometimes 50mm over lumbar spine [46], the clinical significance of this agreement seems

plausible. However, the interpretation depends on another factor: the homogeneity of the distribution of the hypodermis over the sacrum. This is going to be discussed in the next section.

For tissue stiffness parameters, although reliability was not satisfactory for all three parameters: skin, hypodermis, and muscle; the 95% CI level of agreement with the mean of the inter-image analysis of ± 0.33 m/s; ± 0.29 m/s; ± 0.25 m/s respectively, was minimal. In fact, previous studies investigating changes of shear wave velocity values in specific circumstances or disease showed: with prolonged loading in elderly, shear wave velocity of superficial region (mainly skin + hypodermis) over IT varied from 2.5 m/s to 3.3 m/s [31]; contracture strips of the gluteal muscle showed a shear wave velocity of 7.23 m/s vs 1.84 m/s for a healthy muscle at the same position[47]. **Because** the aim of this evaluation is to point out subjects who significantly diverge from normal values, the SWE values for the three regions remain interesting to report. Nevertheless, interpretation should be taken with caution and further investigations are needed to increase reliability. Possible solutions might include operator's training, and taking SWE videos in the transverse and vertical directions, especially for muscle stiffness, since the properties parallel to the fibers are quite different from loading perpendicular to the fibers [48].

2. Young adults vs healthy elderly

The following discussion will highlight observations noted when comparing parameters of the young adults group and the healthy older people for the acquisitions conducted only by the physician. The interpretations cannot be generalized since reliability of measurements was not satisfactory.

For bone parameters, aging is associated with structural, geometric and bone volumetric density changes [49]. It is unclear how that might affect the external shape of the MSC; the similar median values in the boxplot, and the absence of statistical significance of differences between the means for the three parameters might suggest that there are no US changes observable. Therefore, the estimation of these parameters aims to evaluate the impact of bone geometry on tissue deformation independently from age difference.

For the tissue morphology parameters, the median values for both ST and HT were lower for the older group, but no statistical difference was noted between means. In fact, studies have shown that thinning of the skin, associated with age, is observed in subjects with more than 70 years [50] while our older age group had a mean age of 65 ± 2.4 yrs. Nevertheless, the mean ST of the young adults group 3.61 ± 0.55 mm was close to values previously reported for the skin over the sacrum like, for example, Yalcin et al [51] found a mean of 3.2 ± 0.5 mm. Also studies comparing tissue

thickness differences between SCI patients without vs with history of PU showed total thickness average of 15.3 mm vs 9.5 mm over the apex of IT [25]. Thus, the difference is quantifiable, but the challenge remains to determine a risk threshold value at high-risk patients. On the other hand, an observation, not reported in the literature to our knowledge, was noted for the hypodermis thickness distribution over the sacrum. One subject (fig.2b) clearly showed thinning of HT from the lateral to medial spine. Possible causes might be a spinal deformation causing a shift in the hypodermis layer while the skin, loosely bonded to subjacent organs, can slide over and maintain the same thickness [39]. This highlights the importance of measuring the HT directly over the tip of the MSC instead of the thickest region as mentioned in our protocol. In fact, HT is considered as an important parameter affecting internal soft tissue response to load [23] and thus, PU risk.

For the tissue stiffness parameters, median shear wave velocity for skin, hypodermis, and muscle was lower for the elderly group. Only for the muscle the difference showed statistical significance ($p=0.001$). In fact, physiologic aging is associated with a loss of muscle mass starting at the age of 30 [10]. This might be caused by the infiltration of fat tissue and connective tissue into skeletal muscle [52]. Previous studies suggest that this is associated with an increase in muscle stiffness [53] and, with continuous compression, a further increase in muscle stiffness leading to injury [54]. While our results seem contradictory, since we noted a decrease in shear wave velocity between the young and the elderly group, the signal was collected closer to the proximal attachment of the gluteus maximus (lateral to the sacro-coccygeal region) rather than the muscle belly. Moreover, most studies, evaluating tissue stiffness and PU, focused on the variation of stiffness with loading [31], [54], [55]. The complexity and duration of the exam, especially for high-risk subjects, makes it impossible to evaluate a large number in a loading position. That is why we proposed in our study to evaluate tissue characteristics in an off-loading position and determine normal ranges within homogenous groups. While studies suggest that aging is associated with a decline in skin stiffness [9], [56] making it more susceptible to PU, there is no specific threshold value proposed for increased risk. On the other hand, sustained pressure application was associated with an increase in tissue stiffness [31], [57], [58]. The two subjects presenting maximum and minimum skin/hypodermis baseline shear wave velocity in the elderly group (fig2.a; fig2.b) were overweight ($BMI > 25 \text{ kg/m}^2$). It is known that BMI values have an impact on the biomechanical behavior of tissues [59], [60], further investigations are needed to evaluate changes in tissue elasticity associated with BMI changes. Also the mean values of sSWE and hSWE over the sacrum of the elderly group ($2.22 \pm 0.55 \text{ m/s}$ and $1.98 \pm 0.33 \text{ m/s}$

respectively) are close to values reported in the literature (2.5 m/s and 1.8 m/s respectively) for a similar sample of nine healthy volunteers with a mean age of 70.1 ± 4.8 years [31].

3. Limits and perspectives

The lack of reliability of measures is the main limit of our study. This is mainly related to: difficulty in repeating acquisitions on the same anatomic level, definition of parameters, lack of signal stability, and ultrasound expertise. Also, the patient's prone position might be problematic for higher risk subjects. The sample size and the number of operators is also a limitation of this study. However, the protocol we developed is clinically feasible and can be easily proposed to evaluate patients at bedside. The relatively easy palpation of the anatomic landmark (PSIS) allows the exam to be conducted by any physician or nurse. The perspectives include a review of the protocol to increase reliability and an evaluation of higher risk elderly in nursing homes. Also, this protocol can quantify all layers' characteristics including bone, muscle, hypodermis, and skin using only US and SWE. This might serve in - patient specific - finite element modeling since quantifying tissue strain and stress distribution over a bony prominence is essential in determining an injury threshold [23], [55], [61].

Conclusion

In this study, we developed a protocol using US and SWE to assess bone and tissue characteristics over the sacrum in the context of PU prevention in elderly. **It is the** first protocol that combines assessment of all layers over bony prominences using only one imaging technique.

The protocol's reliability was evaluated on a sample of young adults and then tested on a group of healthy older subjects. We provided a thorough description of anatomic landmarks on palpation and US visualization to ensure reproducibility and real clinical application. However, reliability was not satisfactory and further improvements of the protocol are needed. The results comparing the young to healthy older age group suggested that changes related only to age might affect tissue thickness and elasticity more than bone morphology, but this cannot be generalized or quantified before increasing reliability and sample size. On the other hand, an observation in one of the subjects of the elderly group was not found in the literature: a heterogeneous distribution of the hypodermis thickness over the

sacrum. In order to evaluate the use of this tool for PU risk assessment, it is essential to test it on a high-risk sample like elderly in nursing homes or long hospital stay.

Finally, our recommendations for the scientific community - when using US and SWE – are:

- anatomic palpation and US recognition using the curvilinear probe.
- report exact anatomic region and provide proof on the US image.
- when measuring thickness and SWE ensure that acquisition is taken pressure free directly over the bone prominence and not in the surrounding region.
- results cannot be generalized before testing for reliability.

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Conflict of interest

None

APPENDIX 1

Ultrasound and SWE protocol

Position and anatomic landmarks

The volunteer is asked to lie down in the prone position with a cushion under the pubis to reduce lumbar lordosis. The examiner inspects the skin to identify any redness/swelling over the sacral region. Then, he palpates the posterior superior iliac spine (PSIS) and recognizes the continuation of intergluteal cleft representing the midline of the spine.

Curvilinear probe

The curvilinear probe allows a large field of view and better visualization of deep layers. After applying gel on the skin or the probe, the examiner scans the sacral region between the two PSIS in B-mode transverse view. The MSC appears as a reverse V-shaped hyperechoic contour (fig.1a). Sliding the probe lateral to the midline allows the recognition of the round shaped PSIS (fig.1a). An image is captured showing the MSC and PSIS. The region is marked over the skin with a marker or medical tape.

NB: if PSIS is not visible on US the use of sagittal view of the sacrum allows to recognize the anatomic site of the MSC. The examiner can align the site in the middle of the US image and then rotate the probe 90 degrees to return to transverse view.

Linear probe

The linear probe is used to assess the superficial layers over the MSC. A thick layer of gel is applied directly on the midline of the marked level. The probe is then applied in the transverse B-mode view with minimum pressure. Artefacts from air bubbles appear as a linear hypoechoic signal perpendicular to skin layers. The examiner eliminates air bubbles using the probe or by adding and spreading the gel again. An image is captured showing the skin and adipose tissue, and the thick layer of gel over the skin (fig.1b).

The linear probe is also used in SWE mode at the same level with a thick gel layer and minimum pressure. The region of interest (ROI) covering the skin and adipose tissue is chosen, and the examiner waits for a homogeneous signal on the screen, increasing/decreasing elasticity range matching tissue stiffness. One measurement is three videos in SWE of 10 seconds each (or more if signal fluctuates). The last acquisition in SWE mode, for the gluteus maximus muscle, is taken lateral to the sacro-coccygeal region using the same procedure. The anatomic landmark is the sacral horns and sacro-coccygeal ligament described as the “frog sign”. The muscle fibers are described as horizontal echoic lines under the skin and hypodermis (fig1.c).

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