013 **ON THE COMPARISON BETWEEN MRI AND US IMAGING FOR HUMAN HEEL PAD THICKNESS MEASUREMENTS.**

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Abstract: The human heel pad thickness, defined as the shortest distance between the calcaneus and heel skin, is one of the intrinsic factor which must be taken into account when investigating the biomechanics of the heel pad. US and MRI are the preferable imaging modalities used to measure the heel pad thickness as they are both ionizing-free radiations. The aim of this paper is to measure the bone to skin distance of nine heel pad phantoms from MRI and US images, and to compare the results with a true value (TV) in order to find the errors. Paired sample *t-test* was used to compare the measurements. Results showed a statistically significant difference between MRI and US_{1540} (P-value=0.005), and between TV and US_{1540} (P-value=0.013). Furthermore, results showed no statistically significant difference between US_{1530} or MRI and TV (P-value=0.103 and P-value=0.358, respectively), and between MRI and US_{1530} (P-value=0.402). Results confirm the necessity to investigate on the real speed of sound for the heel pad tissues, in order to have realistic measurements when dealing with human heel pads.

I. Introduction

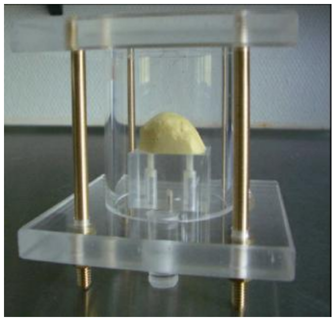
The human heel pad thickness, defined as the shortest distance between the calcaneus and heel skin, is one of the intrinsic factor which must be taken into account when investigating the biomechanics of the heel pad [1,2]. In fact, heel pad thickness has been reported to be an important factor in determining stresses observed in healthy as well as pathological feet [1,2]. Ultrasound (US), Magnetic Resonance Imaging (MRI), Computer Tomography (CT), and X-ray can be used to measure the heel pad thickness. Among those, US (portable, fast scanning time, ionizing-free radiations, low expense), and MRI (ionizing-free radiations) are preferable choices. For US however, measurement errors may occur due to the operator-dependability, the uncertainty of the speed of sound in heel pad tissues as well as the presence of artifacts and angle- dependence. It is thus, necessary to verify the reliability of the imaging techniques by comparing results with a true value. PVA-cryogel, being a suitable material for mimicking the human soft tissues and compatible to both MRI and US imaging [3], was chosen to build artificial heel pad phantoms in order to investigate the reliability of the measurements. The present study concentrates on measuring the bone to skin distance of nine heel pad phantoms from MRI and US images. The comparison with a true value (TV) allows finding the error.

II. Material and Methods

Nine heel pad phantoms were created. They consisted of a plastic calcaneus (only the part which is facing the load in a human foot in normal standing position) fixed to a Plexiglas support and surrounded by heel pad mimicking tissue. Specifically, the heel pad was modeled by using 10% of polyvinyl alcohol (PVA-C) dissolved in water as based material. In order to obtain ultrasound echoes from within the heel pad mimicking tissue, some silica powder was added to the PVA-C [4].

The elastic modulus (E) of PVA-C was controlled by the number of freeze/thaw cycles each model was exposed to. In the present study, the heel pad phantom underwent to three different number of freeze/thaw cycles. The skin-to-bone distances were controlled by adjusting the height of the Plexiglas support of the plastic calcaneus bone. Thus, the models had three different elasticities (E1 = 64 KPa, E2 = 127 KPa, E3 = 161 KPa) combined with 9 different known skin-to-bone distances.

The true value (TV) of the skin-to-bone distance was calculated from the dimensions of the mould and the phantom. Figure 1 shows a typical mould used to create the heel pad phantom, as well as the typical heel pad phantom.



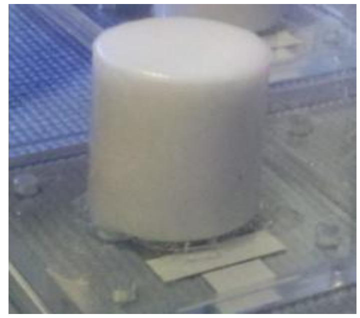


Fig.1 Typical heel pad mould Fig.2 Typical heel pad phantom

All heel pad phantoms underwent both 3D MRI [3T Siemens Magnetom Verio, T1 Vibe isotropic sequence. TE/TR=5.41/12.4 ms, flip angle 10 degrees, TA=5 min, slice thickness=0.60 mm], and 3D US (LOQICE9-GE healthcare, 12MHz). Each phantom was scanned twice from the top with the US transducer in both longitudinal and transversal position by the same experienced doctor, as shown in Figure 3. Figure 4 shows one of the heel pad phantom placed inside the coil in the MRI scanner. All the images were stored in DICOM format.

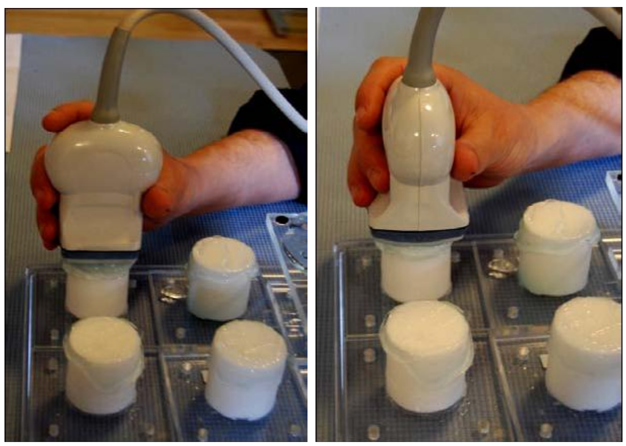


Fig.3 US measurements with the transducer in longitudinal (on the left) and transversal position (on the right)

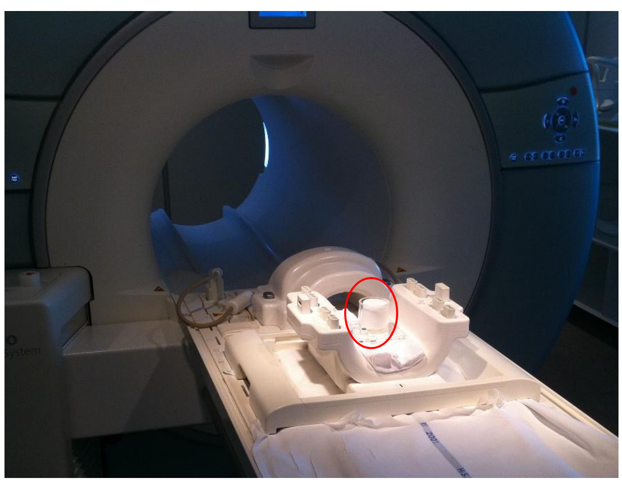


Fig.4 Heel pad phantom (marked by the red circle) placed inside the coil in the MRI scanner

All DICOM images were processed by using MATLAB tools, so that 3D data were extracted. For each heel pad phantom the contours of both the calcaneus and the top of phantom were delineated on each plane with an automatic procedure, as shown in Figure 5. Each image corresponded to a matrix of pixel values from 0 to 1, which determined the contours of calcaneus and the top of phantom. Specifically, for the US images the calcaneus was represented by pixels with values higher than 0.9, whereas the top of the phantom by pixels with values higher than 0.6. Each column of each image was read starting by the top, and the first pixels superior to those thresholds were stored. Then, the coordinates of the highest point of calcaneus were found automatically, and the skin-to-bone distance was found. A 3D visualization was made for each phantom, as shown in Figure 6.

The standard value of the speed of sound used by the ultrasound scanner for human tissue is $1540 ms^{-1}$, but for PVA-cryogel it ranges from $1520ms^{-1}$ to $1540\ ms^{-1}$ [3]. Therefore, for each heel pad phantom the thickness was calculated also by using a speed of sound of $1530ms^{-1}$.

Paired sample *t-test* was used to compare the thickness measured by MR or US images with the TV. A P-value less than 0.05 was accepted as significant, thus the difference was not negligible.

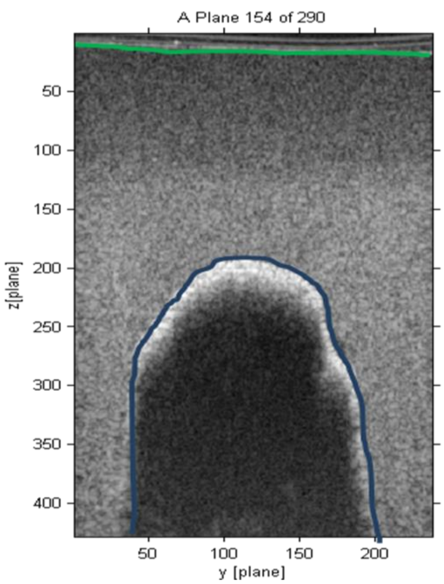


Fig.5 US image of a typical heel pad phantom

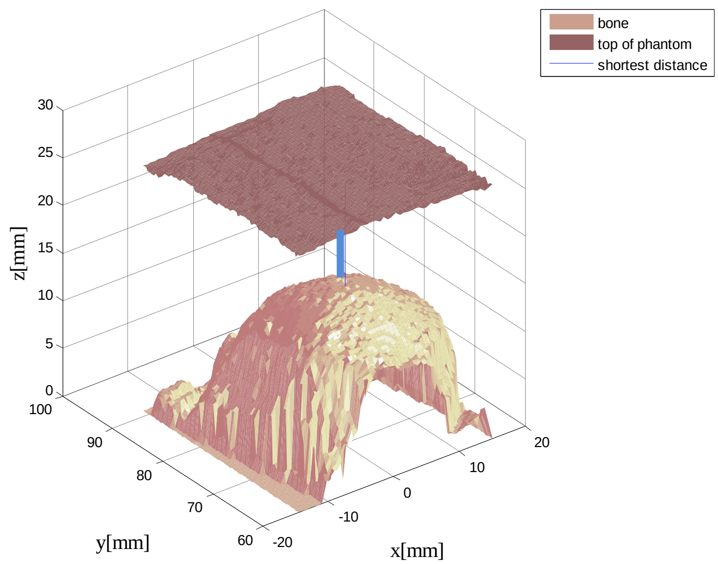


Fig.6 3D reconstruction of a typical heel pad phantom.

III. Results

Table 1 shows the values of the thickness of all 9 heel pad phantoms measured from US_{1530}, US_{1540}, MRI and TV. Figure 7 plots with histograms the values reported in Table 1. Figure 8 shows for each phantom the difference between the true values and measurements done with US and MRI.

When distance measurements are done from MRI and/or US images the absolute error expressed in millimeters should not depend on the distance measured. This can be verified by plotting the error made by each technique as a function of the true value (Figure 9). This plot shows that the maximum error made by US_{1540}, US_{1530} and MRI was 0.62 mm (3.70%), 0.50 mm (2.98%) and 0.54 mm (3.22%, respectively). From data shown in Figure 9 it was also possible to find that the average errors ± standard deviations made by US_{1540}, US_{1530} and MRI were 1.8±1.8 (%), 1.2±1.8 (%), 0.9±2.4 (%), respectively.

The statistical analysis showed that there was statistically significant difference between MRI and US_{1540} (P-value=0.005) as well as between TV and US_{1540} (P-value=0.013). Furthermore, results showed that there was no statistically significant difference between US_{1530} or MRI and TV (P-value=0.103 and P-value=0.358, respectively), and between MRI and US_{1530} (P-value=0.402).

Table 1 Thickness measured for each phantom from all techniques

Heel pad phantom	US_{1540} (mm)	US_{1530} (mm)	MRI (mm)	TV (mm)
1	13.15	13.06	12.45	12.61
2	13.12	13.04	12.60	12.63
3	13.05	12.97	12.60	13.14
4	17.36	17.25	17.29	16.74
5	15.73	15.63	15.23	15.56
6	15.68	15.57	15.09	15.59
7	18.94	18.81	18.89	18.54
8	18.54	18.41	17.72	18.18
9	17.35	17.23	17.43	17.41

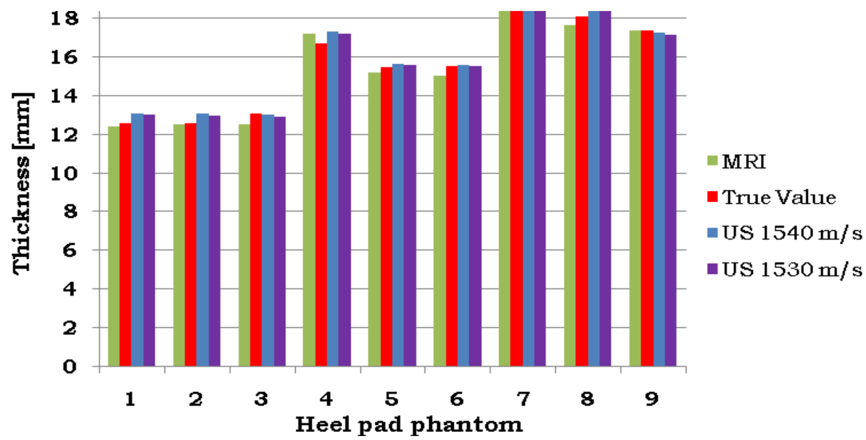


Fig 7 Thickness of all phantoms measured from all techniques

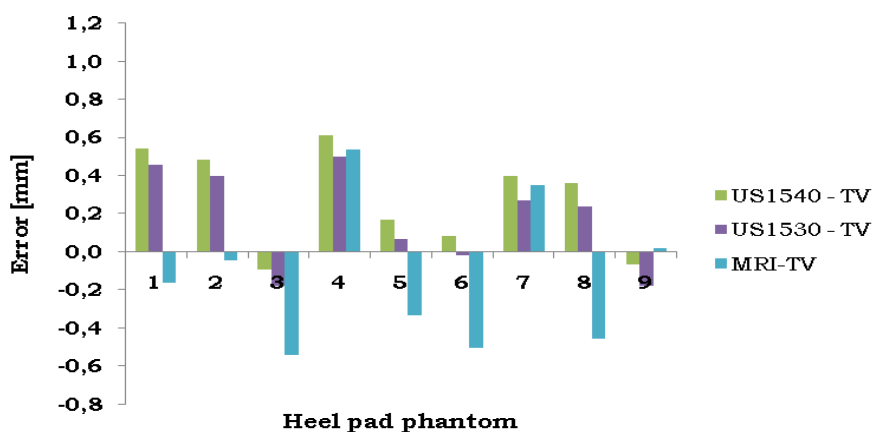


Fig 8 Difference of measurements between US or MRI and the true value (TV)

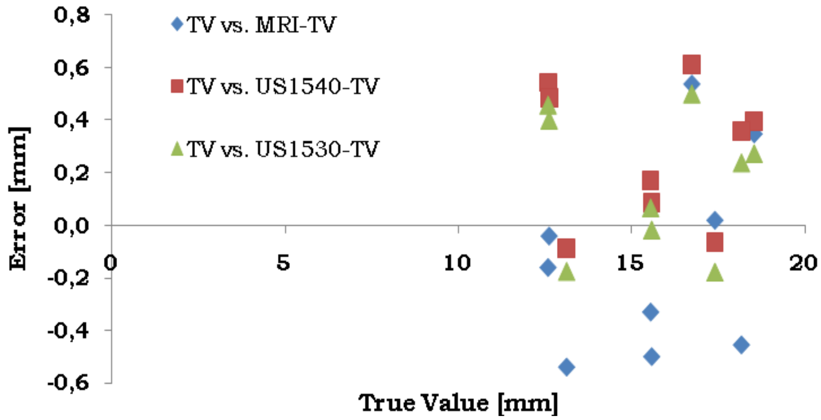


Fig 9 The difference of the measurement between the true value and imaging technique (MRI and US) is plotted as a function of the True Value.

IV. Conclusions

From Figure 8 it is clearly visible that MRI measurements underestimate the phantoms thickness for six phantoms out of nine, while US_{1540} overestimates for seven phantoms out of nine. Furthermore, the thickness calculated with US_{1530} is always lower than US_{1540}, as is expected. Figure 9 indicates that for each imaging technique some systematic errors might be present. For US measurements the main uncertainty is the average speed of sound assumed by the scanner (1540ms^{-1}), but errors might be due also to the angle-dependency as well as the operator-dependency. Measurements errors for TV might be reduced by using a true value extracted from µ-CT images by applying the same 3D estimation procedure. In this case 3D reconstruction obtained from MRI, US and µ-CT images should be overlapped in order to verify whether the measurements are done at the same place of the calcaneus and top of the phantom. Finally, the measurement error for MRI might be due to the sequence applied, and a possible optimization might reduce the uncertainty of the measurements.

The present study confirms, once minimized the measurement errors before mentioned, the necessity to investigate on the real speed of sound for the heel pad tissues, in order to have realistic measurements when dealing with human heel pad.

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