Quantification of *in vivo* muscle elastic anisotropy factor by steered push beams

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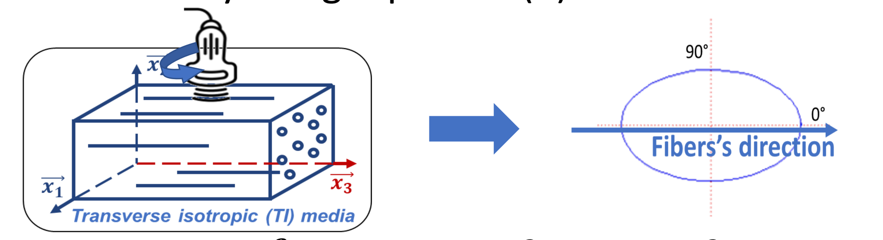
Introduction

Ultrasound (US) elastography has recently emerged as a noninvasive modality to quantify soft tissue stiffness. Classically, it is performed using push beams (PB) that generate shear waves (SW) which are then followed by ultrafast US imaging. In isotropic tissues, the SW velocity (V) is directly related to stiffness (μ) by the relationship: $\mu = \rho.V^2$. However, in transverse isotropic (TI) tissues such as skeletal muscle two SW modes can be generated [1, 2]: (1) a shear horizontal (SH) and (2) a shear vertical (SV) wave mode. In this case, the SWV cannot be directly linked to a single µ when SW propagation direction and polarization are not either parallel or perpendicular to the tissue symmetry axis. This scenario typically occurs in pennate muscles. Recently, Ngo *et al.* proposed a novel method that uses steered PB to tackle this limitation [3]. Here, we combined steered PB with SV mode of SW propagation to fully characterize the mechanical properties of TI muscle tissue. This allowed us to directly estimate the tensile anisotropy χ_E and to assess its behavior during submaximal contractions. We hypothesized that this parameter can help to characterize muscle structure and function properties more comprehensively.

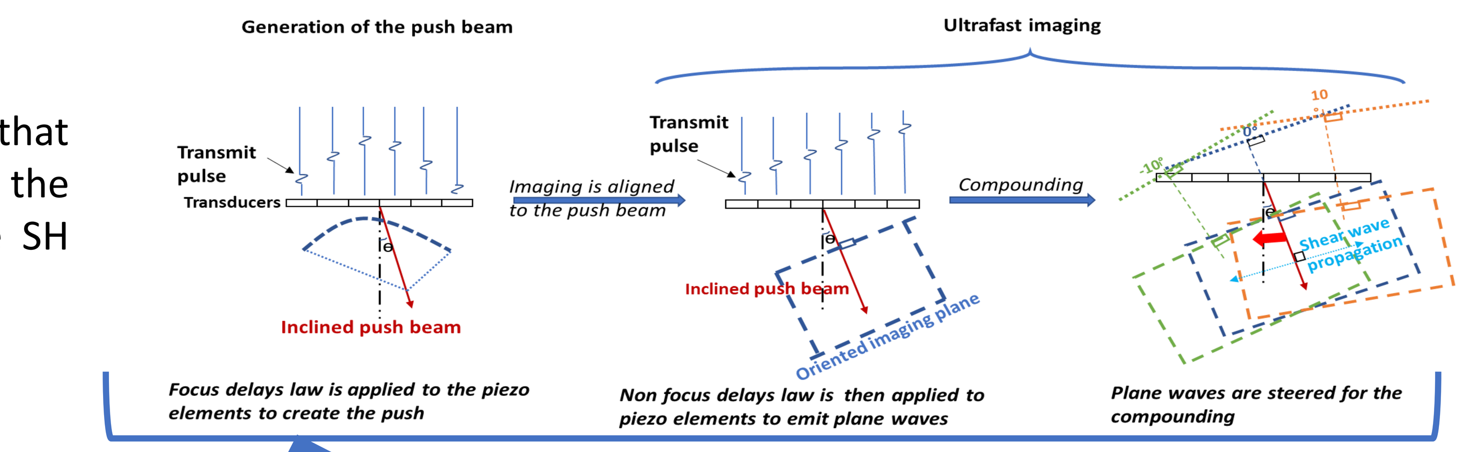
Methods

1/ For fusiform muscles, classical SSI method that consists of rotating the probe at the surface of the muscle allows to quantify the velocities of the SH wave mode by using equation (1) :



$$\mu_{SH}(\psi) = \rho v_{SH}^2(\psi) = \mu_{\parallel}\cos\psi^2 + \mu_{\perp}\sin\psi^2 \quad (1)$$

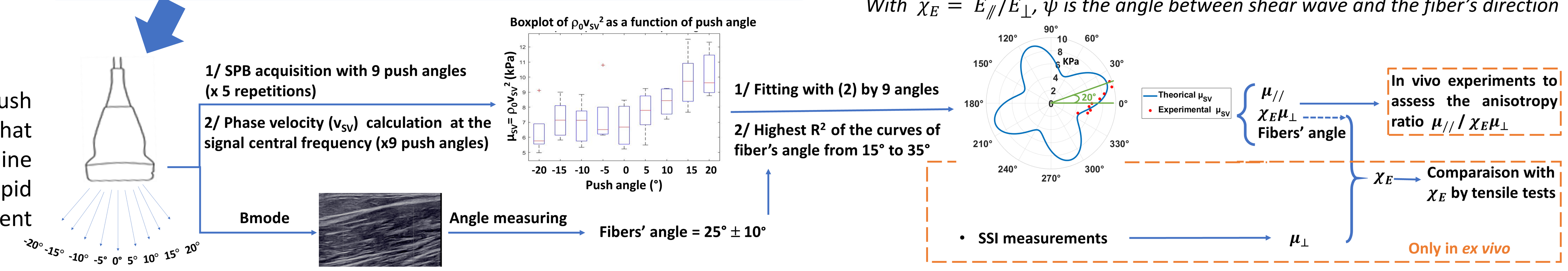
2/ For pennate muscles, we used steering push beams (SPB), which is an elastography method that applies the delay laws on a linear probe to incline the ultrasound push. This method enabled a rapid quantification of anisotropy factor χ_E of different muscles during different contraction states.



The sequence was conceived on an ultrafast ultrasound device (Mach30, Hologic) with a 6 MHz linear probe [3]. By inclining the push beam, the vertical shear wave (SV) is generated [2]. The SV velocity is dependent on the angle of shear wave direction regarding the fiber's direction according to the equation (2) [3].

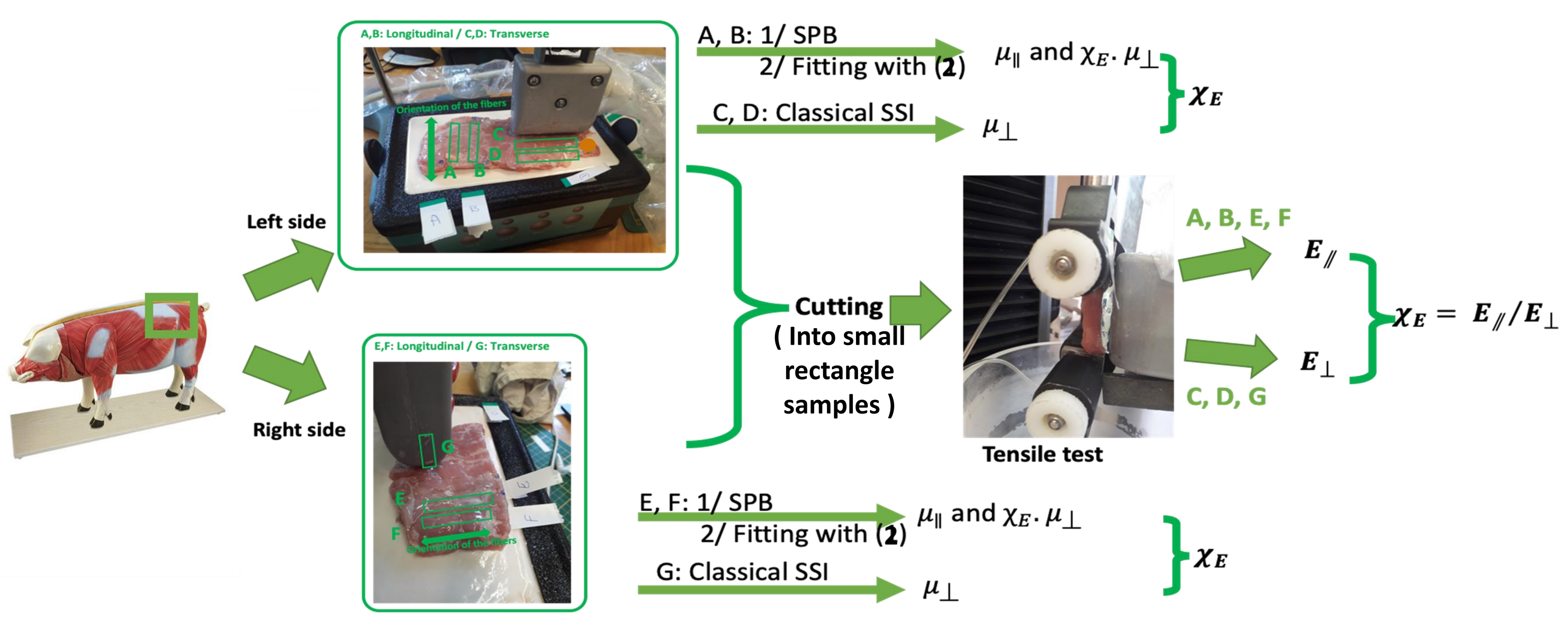
$$\mu_{SV}(\psi) = \rho v_{SV}^2(\psi) = \mu_{/\!/} + 4(\chi_E.\mu_{\perp} - \mu_{/\!/})sin(\psi)^2 cos(\psi)^2 \ (2)$$

With $\chi_E = E_{/\!/}/E_{\perp}$, ψ *is the angle between shear wave and the fiber's direction*



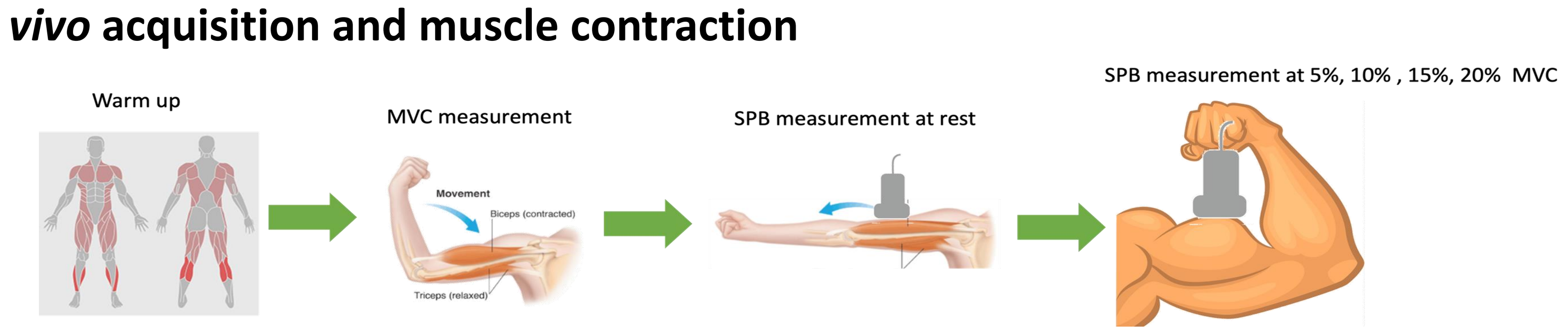
Protocols

1. *Ex vivo* validation of χ_E estimation



- χ_E could be calculated by the SPB method coupled with classical SSI. Thanks to tensile test which can only be carried out *ex vivo*, this result could be validated, that shows the reliability of SPB method.

2. *In vivo* acquisition and muscle contraction



- 2 healthy volunteers (young adults)
- 2 muscles: fusiform (*biceps brachii*) and pennate (*medial gastrocnemius* (MG))
- An ergometer was used to measure the maximal voluntary isometric contraction (MVC). A visual feedback was used to control the force levels, expressed as % of MVC
- The results obtained from SPB were assessed regarding muscle contraction states

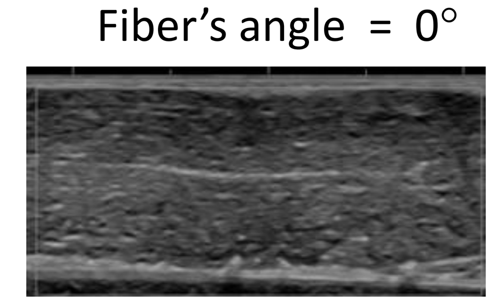
A set up for acquisitions on the MG

Results

1. Validation of χ_E estimation in *ex vivo* muscle

(a/ left side b/ right side)

a/ Fiber's angle = 0°

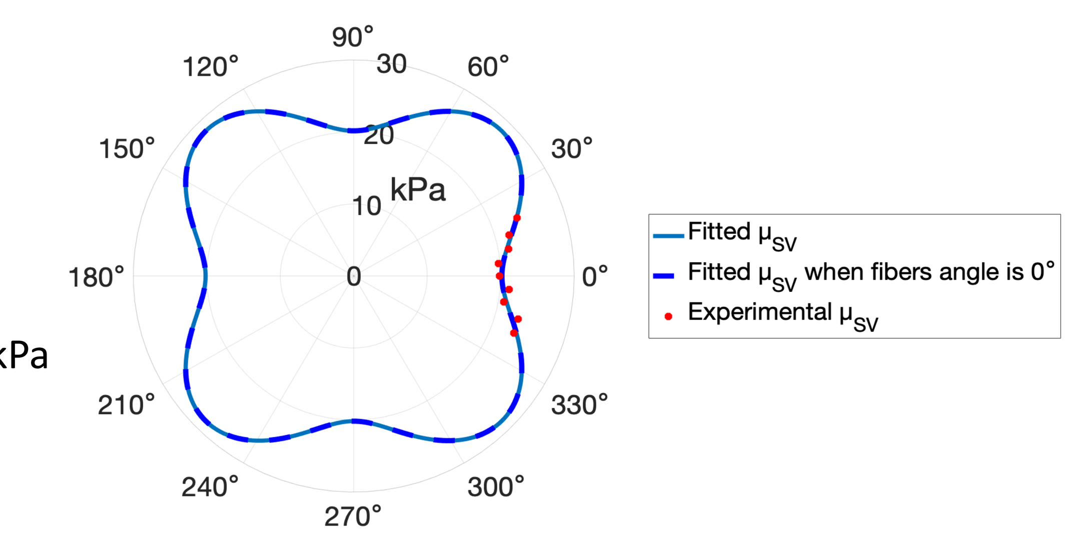


Bmode of the left extracted porcine iliopsoas

1/ SPB → **2/ Fitting with (2)**

$\mu_{/\!/} = 20.05 \pm 0.16$ kPa

$\chi_E.\mu_{\perp} = 28.64 \pm 0.23$ kPa



μ_{SV} *as a function of fiber's angle*

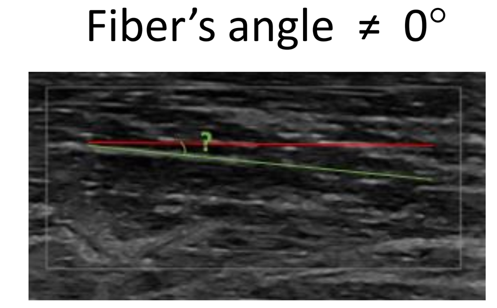
SSI : $\mu_{/\!/SSI}$ = 21.65 ± 0.08 kPa and $\mu_{\perp SSI}$ = 9.33 ± 0.36kPa

➡ χ_E = 28.64/9.33 = 3.07 ± 0.13 • Validation from tensile test: $\chi_E = E_{/\!/}/E_{\perp}$ = 2.90

b/ SPB coupled with SSI : χ_E = 2.89 ± 0.23 • Validation from tensile test: $\chi_E = E_{/\!/}/E_{\perp}$ = 2.93

2. Analysis of *in vivo* measurements

Fiber's angle ≠ 0°

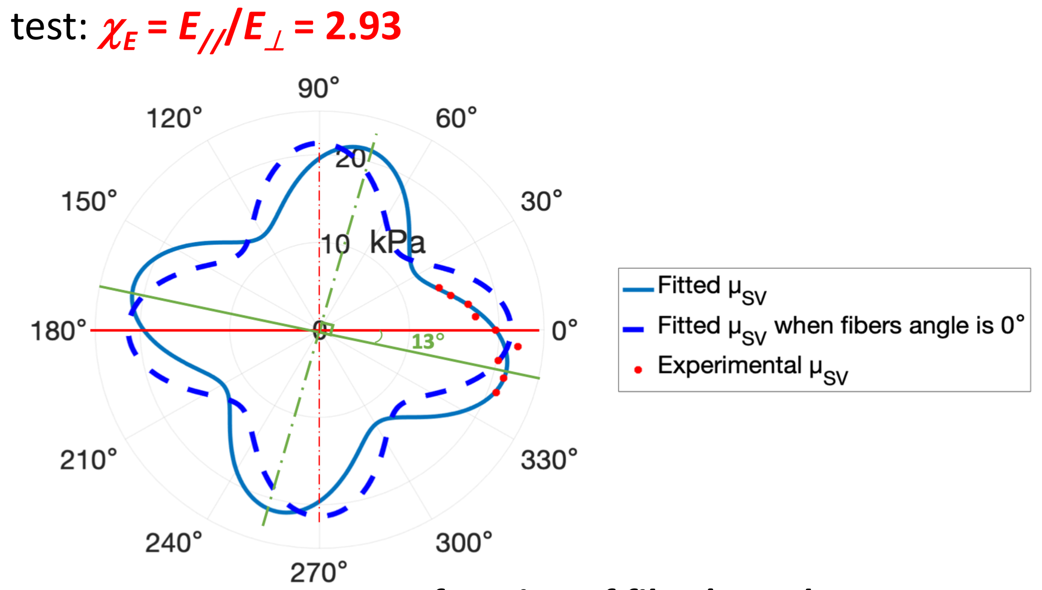


Bmode of a human biceps brachii at rest

1/ SPB → **2/ Fitting with (2)**

$\mu_{/\!/}$ = 21.32 kPa

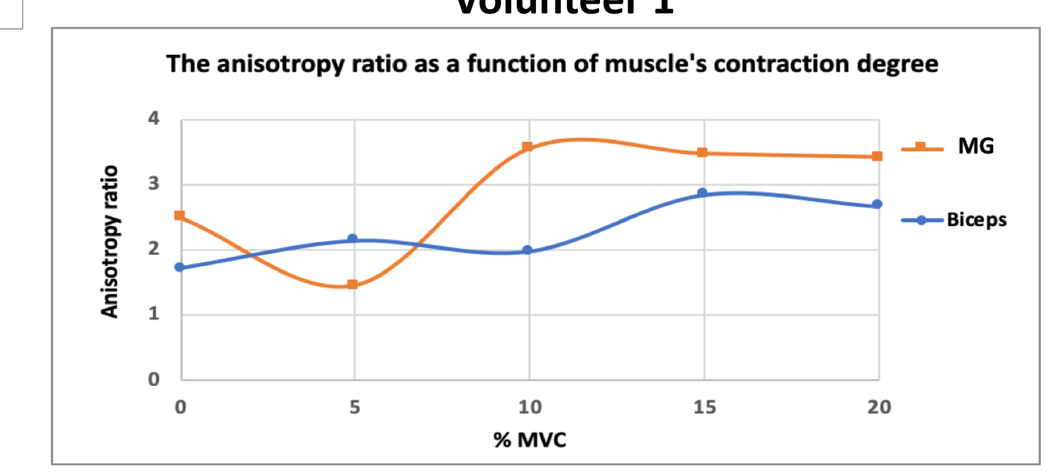
$\chi_E.\mu_{\perp}$ = 12.42 kPa



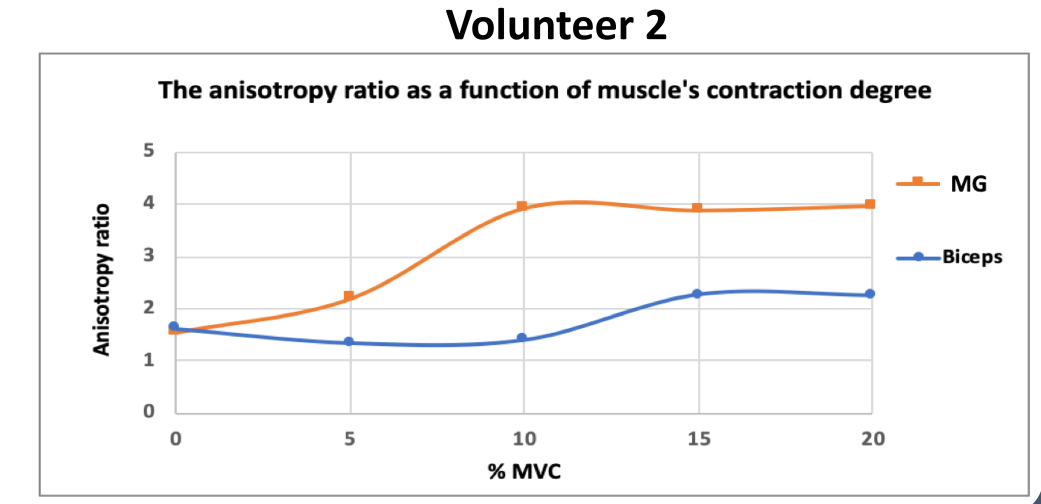
μ_{SV} *as a function of fiber's angle*

The ratio $\mu_{/\!/}/\chi_E.\mu_{\perp}$ was used to evaluate the effect of anisotropy on muscle stiffness during contraction of MG and *biceps brachii*, knowing that fiber's orientation changes with the muscle's contraction state.

Volunteer 1



Volunteer 2



Discussion

- The measurement of χ_E was preliminarily validated by tensile test. Thus, it can be said that SPB is a reliable and promising method. That paves the development of a faster assessment of the shear anisotropy factor by the SPB method, which is carried out within a single acquisition.
- There is a difference between the 2D fiber's angle measured from the Bmode images (~10°) and the fiber's angle determined by our elastography method (13°). That can be explained by the fact that the ROIs selected in our method are small, thus, fiber's angle found is only a local value.
- The ratio $\mu_{/\!/}/\chi_E.\mu_{\perp}$ tends to increase as the muscle contraction increases. That was observed in fusiform and pennate muscles but with different magnitude. Further studies are required to confirm this result and better understand this phenomena.

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[1] Rouze PMB 2020, [2] Knight IEEE TMI 2021, [3] Ngo IEEE IUS 2021