Utilization of Multi-Foci ARFI Imaging to Generate Larger Tendon Displacement

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Introduction

Acoustic Radiation Force Impulse (ARFI) imaging is an ultrasound technique that generates a localized force onto the tissue of interest and the resulting tissue displacement is measured[1]. The utility of ARFI imaging is not well understood for stiff, anisotropic biological tissues such as tendons. Conventional full-frame ARFI imaging utilizes narrow beams for better image resolution, but limits the acoustic radiation force applied to the tissue. Multi-Foci beamforming allows for a more powerful and focused beam of acoustic radiation force.

Objective

Evaluate differences in ARFI tendon displacement before and after tendon injury using a Multi-Foci and Full-Frame ARFI imaging approach.

Materials & Methods

- 4 fresh-frozen, porcine extensor tendons
  - ➢ Cross-sectional area → laser scanner (Next Engine 3D Scanner HD)

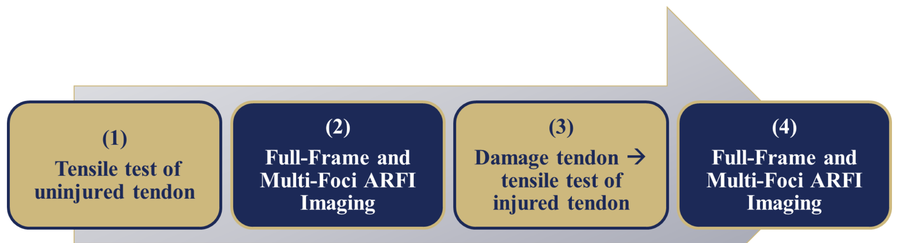

Figure 1: Overview of study design.

1) Tensile Test

- Preload = 1N → Preconditioning = 1-10N for 10 cycles → Load to 100N
  - ➢ Output parameter = linear region modulus

2) ARFI Imaging

- Research ultrasound (Verasonics, VDAS V-1 Model) and linear array transducer (ATL L7-4)
- Full Frame and Multi-Foci ARFI Imaging (Figure 2)
  - ➢ Beam focused at elevation focus (25 mm) for 1000 cycles at 5.2 MHz (duration = 192 µs)
  - ➢ Tendon wrapped in muscle and loaded
    - Loading Levels: 0.1, 0.25, 0.5, 0.75 and 1 MPa
  - ➢ 3 sequential images obtained at each stress level without altering test setup
  - ➢ Displacement measured using Loupas algorithm[2]
    - Repeatability: < 0.2 µm
- Output parameter: Average ARFI tendon displacement across 3 sequential images

3) Mechanical Damage → Repeat tensile test step

- Compressive loading = 1-100N for 40 cycles

4) Repeat ARFI Imaging Protocol

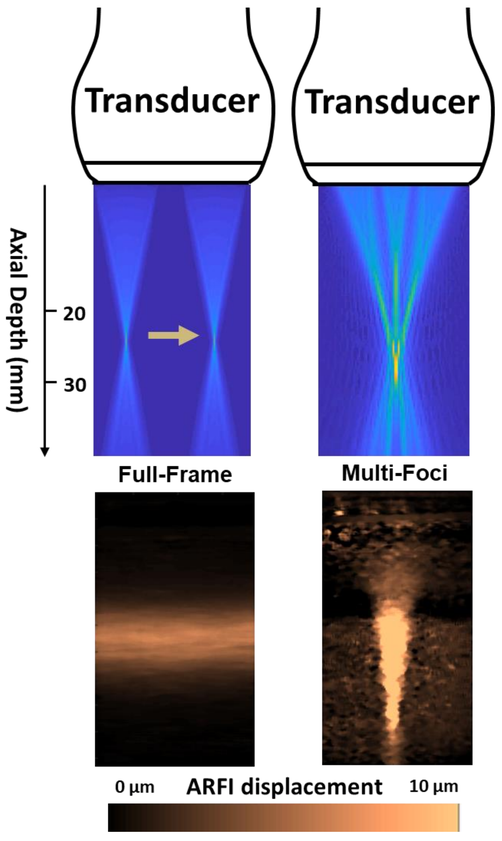

Figure 2: Full-frame uses 1 beam across transducer aperture width. Multi-Foci divides aperture into 3 beams and focuses at a precise location.

Results

- ARFI tendon displacement: Multi-Foci > Full-Frame ($p < 0.05$) (Figures 3 & 4)
  - ➢ Average across all conditions
    - Multi-Foci: 1.6 ± 0.4 µm
    - Full-Frame: 0.6 ± 0.3 µm
- Linear region modulus decreased on average 43% after damaging
  - ➢ Un-injured: 347 ± 100.7 MPa
  - ➢ Injured: 195.4 ± 47.8 MPa
- Small difference in ARFI tendon displacement before and after injury (Figure 3)
  - ➢ Average across all loading levels
    - Multi-Foci: < 0.2 µm
    - Full-Frame: < 0.1 µm

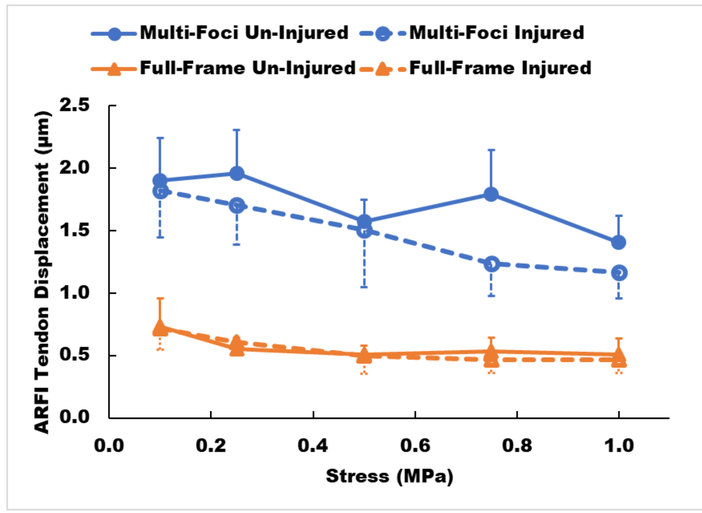

Figure 3: ARFI tendon displacement data (Avg ± SD). Blue circles indicate Multi-Foci approach. Orange triangles indicate Full-Frame approach. Dashed lines indicate injured tendons

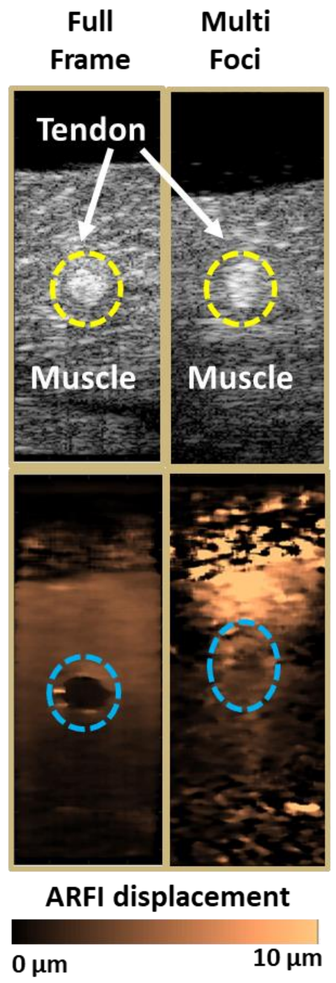

Figure 4: Full-Frame: less ARFI displacement within stiff tendon than surrounding softer muscle. Multi-Foci: higher ARFI tendon displacement

Discussion

- Multi-Foci ARFI Imaging: Novel method to generate more force to displace stiff tendons
  - ➢ ARFI imaging provides local tissue information, but traditionally used for soft isotropic tissues (ie. breast modulus ~10s kPa vs tendon modulus ~100s MPa)
- Multi-Foci ARFI imaging generated 3 times more tendon displacement than Full-Frame
  - ➢ Magnitude of tendon displacement is measurable, but less than breast and abdominal tissues (up to 10 µm) [1-4]
- Larger magnitude displacements may differentiate between un-injured and injured tendons, but further development needed
  - ➢ Differences at certain stress levels (0.25 and 0.75 MPa) greater than 0.2 µm repeatability

Future Directions

- Correlate ARFI displacements with mechanical properties of tendons

Acknowledgements

Support from the University of Pittsburgh Swanson School of Engineering, Department of Bioengineering, Orthopaedic Surgery, and NSF-GRFP No. 1247842

References

[1] Nightingale et al. Ultrasound Img. 2002
[2] Pinton et al. IEEE Trans Ultrason Ferroelectr Freq Control. 2006
[3] Fahey et al. Ultrasound Med Biol. 2005
[4] Nguyen et al. Ultrasound Med Biol. 2017