The AutoQual ultrasound elastography method for quantitative assessment of lateral strain in post-rupture Achilles tendons

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This paper presents the AutoQual elastography method: a novel algorithm that improves the quality of 2D displacement field calculation from ultrasound radio frequency (RF) sequences of acutely ruptured Achilles tendons to determine image-lateral strain fields and has potential use for ligaments and muscles. This method uses 2D bicubic spline interpolation of the RF signal, Quality Determined Search, Automatic Search Range and Adaptive Block Size components as a novel combination that is designed to improve continuity and decrease displacement field noise, especially in areas of low signal strength. We present a simple experiment for quantitatively comparing the AutoQual method to a multiscale (MS) elastography method from ultrasound RF sequences of a 5% agar phantom for rigid body motion and known lateral strain loads with speeds up to 5 mm/s. We finally present examples of four in vivo Achilles tendons in various damage states and with manual or artificially controlled passive flexion of the foot. Results show that the AutoQual method offers a substantial improvement on the MS method, achieving similar performance for rigid body tracking at all speeds, a lower normalized square error at all strains induced and a more continuous strain field at higher compression rates. AutoQual also showed a greater average normalized cross correlation for image blocks in the area of interest, a lower standard deviation of the strain field and a visually more acceptable point tracking for in vivo examples. This work demonstrates lateral ultrasound elastography which is robust to the complex passive motion of the Achilles and to various imaging artifacts associated with imaging tendon rupture. This method potentially has a wider clinical application for assessing in vivo strains in and hence mechanical function of any near skin surface tissues that are longitudinally loaded.

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1. Introduction

Tendons are highly anisotropic soft tissues used for force transmission and mechanical energy utilization. Mechanical information about these tissues in vivo is difficult to obtain and current clinical measures are largely limited to subjective questionnaires on pain response, movement restriction and spatial measures (Robinson et al., 2001; Kearney et al., 2012).

There is a strong clinical desire for a reliable, quantitative method for evaluating functional properties of ruptured tendons (and further use for ligaments and muscles) as rerupture rates are high at 3–15% (Wilkins and Bisson, 2012; Cetti et al., 1993). Measures could be used to compare patient groups with different treatments, assess individual subjects’ response to treatment or diagnose chronic conditions. Mechanical properties may be a useful metric (Bey and Derwin, 2012) and have been shown to be affected by mechanical stimulation and other factors over that period (Andersson et al., 2012; Schepull et al., 2007).

Imaging methods have been used by several groups to obtain quantitative measures of strain, stiffness or elastic modulus under repeatable loading conditions. One method involves implanting tantalum beads to measure displacement differences under using CT imaging (Schepull et al., 2007), although this has limited clinical acceptability due to the invasive nature, x-ray dosage and concerns of bead migration affecting results.

Ultrasound imaging is safer and more available, and other methods involve measuring strain by tracking features (Gerus et al., 2011; Stenroth et al., 2012) or free tendon substance (Arndt et al., 2011) with known loads, passive motion or maximum voluntary contraction. An example of sagittal-plane B-mode image of a healthy Achilles tendon with axes defined as used in this paper is shown in
allows a lower stiffness ‘toge region’ in the 0–3% strain range before a stiffer and more linear response in the functional strain range (Abrahms, 1967). In recently ruptured tendons this toe region will not be apparent as long collagen fibers are disrupted.

2. Aims

Multiscale methods for measuring tendon strain post-rupture have previously been used by our group (Brown et al., 2012; Alsousou et al., 2012) but are vulnerable to show discontinuities, particularly in areas of low signal strength. In this paper we propose a new US elastography method that is more appropriate for measuring image-lateral strain in vivo in damaged Achilles tendons. The aims are to:

- Describe the elements of the innovative ‘AutoQual’ method.
- Present experimental methods for comparing algorithms using phantom block controlled rigid body motion or strain and to use these to compare the AutoQual and Multiscale (MS) methods.
- Qualitatively demonstrate clinical examples where the AutoQual method reduces errors found in MS elastography for recently ruptured Achilles tendons.

3. Methods

The AutoQual block matching method incorporates several elements that enhance robustness and repeatability, improve the continuity and decrease the error of the calculated displacement field, increase the displacement field size and reduce the dependence on user specified search regions. We also briefly describe the MS method used for comparison.

3.1. The AutoQual method

AutoQual is a single RF-signal scale block matching algorithm using the Quality Determined Search (QDS) method (C2hen et al., 2009) where the displacement of an initial small sub-set of ‘seed’ blocks is evaluated, then the neighboring blocks to those with the best correlation are evaluated next with the value of the parent seed block used as an initial estimate. The process is then repeated with calculations being cascaded from areas of good correlation into the areas of low correlation.

We used Normalized Cross Correlation (NCC) rather than the Sum of Square Difference (SSD) cost used by Chen et al. as we found that some of the erroneous small areas of high displacement values are eliminated or greatly reduced in our implementation.

For sub-pixel tracking, 15 parameter 2D bicubic spline interpolation of the RF signal was used (Viola et al., 2008) as shown:

$$f_{ij} = \sum_{k=0}^{3} \sum_{j=0}^{3} a_{ijk} \cdot x^k \cdot z^j$$

$$+ \sum_{k=3}^{6} \sum_{j=0}^{6} a_{ijk} \cdot x^k \cdot z^j$$

$$+ \sum_{k=0}^{6} \sum_{j=3}^{6} a_{ijk} \cdot x^k \cdot z^j$$

$$+ \sum_{k=0}^{6} \sum_{j=0}^{6} a_{ijk} \cdot x^k \cdot z^j$$

(1)

where 0 ≤ x ≤ 1, 0 ≤ z ≤ 1, f is the continuous value function from a point at (ij) described by coefficients k. The NCC cost is a then made as continuous function of x and z and solved numerically to find the local maximum.

An RF resolution block size of 51 × 25 pixels z by x (approximately 2 mm by 4.75 mm, note the pixel resolution is rectangular) was used, which is within the literature range of reported block sizes (Lopata et al., 2009). The large block size in the x-direction enhances matching signals with lateral displacement while the smaller z-direction is required to reduce error around shearing boundaries expected between the tendon and deeper material. A high block overlap was used with centers spaced at 15 × 2 pixels.

As the QDS provides an initial estimate of the position, we define the search region centered at this initial estimate rather than at zero displacement, a feature we call ‘Automatic Search Range’. A small search range is used: ± 5 pixels [0.077 mm] by ± 1 pixel [0.149 mm] (depth by width). Larger displacements are still found as continuity within the tissue allows initial estimates to propagate.
along displacement gradients. Reducing the search range has the additional benefit of reducing the computational effort required (although this is not an objective of this work) and reduces the possibility of finding an incorrect local maximum NCC. This is particularly effective in areas of low signal strength.

Adaptive Block Size (ABS) allows the search algorithm to use smaller windows when at the edge of the specified search region, defined as

\[
X_{\text{min}} = \min \{ 1; i + B_i - 1 \} \\
X_{\text{max}} = \min \{ 5; i + B_i \} \\
Z_{\text{min}} = \max \{ 1; j - B_j - 1 \} \\
Z_{\text{max}} = \min \{ 5; j + B_j \}
\]

where \( S \) is the size of the search region, \( B \) is half the block size (assumed odd, rounded down) and \( X \) and \( Z \) are the coordinates used for the block.

This allows more continuous displacement fields to be generated around the image edges and makes the algorithm more robust by being less dependent on user specified search ranges as displacements larger than the search range can still be found.

For each interframe displacement field a \( 5 \times 5 \) pixel median filter is then used in order to reduce noise.

The whole sequence displacement field is found by multiframe summation of all interframe displacement fields. To obtain a continuous tracking of each point, the interframe displacement fields are interpolated to find the values at the locations described by the sum of the previous displacements in the sequence as described by

\[
D_i(k, n + 1) = D_i(k, n) + d_i(j, i, k, n) + D_i(j, i, n, k) + D_i(j, i, n, k)
\]

where \( D \) is a matrix of cumulative displacement; \( x \) and \( z \) are the directions relative to the prior positions at frame \( n \) and positions \( i \) and \( k \); \( D_x \) and \( D_z \) are the orthogonal components of \( D \); \( d \) is the non-cumulative frame-to-frame displacement field at frame \( n \) in and positions \( i \) and \( k \).

Local strain is estimated by fitting independent linear trends in each of the axial and lateral directions to specified 2D subsample windows of the 2D total displacement field. The polynomial fits are weighted by the NCC of the displacement estimates at each point. The values of the gradients are ascribed to the central sample position to build up the axial and lateral strain fields. The polynomial fit acts as additional regularization to the displacement field, reducing the contribution of sudden steps but adding arbitrary smoothing which reduces peak strain values.

3.2. The Multiscale method

The MS method used for comparison was formulated in a similar way as the AutoQual method, but with a wider, origin-centered search range, a fixed block size and independent multiscale block-displacement calculation. The MS method first calculates the displacement fields from a scale of RF resolution non-log compressed signal envelope, then uses this finding to initialize a higher scale and then the RF data. This combines the ability of low-scale matching to capture large movements and of high-scales to refine the accuracy.

The MS search range was \( \pm 30 \) pixels (0.4621 mm) in the \( x \)-direction and \( \pm 2 \) pixels (0.30 mm) in the \( z \)-direction. This was based upon experience from in vivo sequences and not optimized for each sequence.

4. Experiments

Our experimental method for comparing the algorithms uses phantom experiments with controlled motion and in vivo data from scans of four subjects. The ultrasound system was a Zonare Ge one (ZONARE Medical Systems, Inc., Mountain View, CA) with a L14-5 linear transducer, central frequency 12 MHz, frame rate 13.4 Hz. Human data acquisition was approved by the Oxfordshire Ethics Committee B (reference 09/H0605/78) and registered at the International Standard Randomized Controlled Trial (ISRCTN-93608625). It is conformed with the current revision of the Declaration of Helsinki and ICH Guidelines for Good Clinical Practice (CPMP/ICH/135/95) July 1996.

The phantom was a 80 mm sided cube made of 5% agarose gelatin with talc powder to provide texture in the US image. The phantom was cast in a custom mold that allowed it to be clamped in a vertical mechanical testing machine (Zwick/Roell 2005) which provided ground truth for displacement and strain calculation. The US probe was mounted parallel to the direction of motion (Fig. 2). A minimal contact gap and transmission gel assured good acoustic contact.

4.1. Rigid body motion phantom tests

The phantom was displaced by 3.5 mm (with zero strain) at set constant speeds in the range 1.0–5.0 mm/s, representative of slow passive motion of the Achilles tendon. To minimize mechanical error, such as probe stick, we report the absolute error of the steady state speed compared to the testing machine rather than displacement error. Three repeated measurements were taken for each speed and the probe was repositioned between each.

4.2. Controlled strain phantom tests

The first strain test attained a range of strains (1.25–4.375%) at a constant grip-to-grip speed of 1.5 mm/s to report the normalized square error (NSE) from ground truth as shown in Eq. (4). The NSE was analyzed for the top 10 mm depth of phantom block as is the typical depth for Achilles tendons and sequences were from decompression cycles to simulate elongation:

\[
\text{NSE} = (\sigma_E - \sigma_N)^2 / \sigma_N
\]

where \( \sigma_E \) is the average strain computed by elastography and \( \sigma_N \) is the notional average strain based on the testing machine grip.

The second strain test assessed the uniformity of the strain fields which attained a constant strain target of 4.375% (3.5 mm decompression) using speeds 1.0–5.0 mm/s was obtained and standard deviation of strain calculated from the two elastography methods. As a uniform strain is expected, higher standard deviations indicate increased variability.

4.3. In vivo testing

Four in vivo sequences of Achilles tendons were acquired with controlled passive dorsiflexion from a force-neutral foot position (approximately 110°) and 1–5 mm of tendon movement using either a motorized foot device or manual clinician manipulation (Table 1). The probe was held in contact with the subject by an experienced clinician. Passive motion has been shown to produce

Table 1

<table>
<thead>
<tr>
<th>Subject</th>
<th>Subject description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Week 0 rupture, manual motion</td>
</tr>
<tr>
<td>B</td>
<td>Week 6 rupture, controlled motion</td>
</tr>
<tr>
<td>C</td>
<td>Healthy Tendon, controlled motion</td>
</tr>
<tr>
<td>D</td>
<td>Week 0 rupture, controlled motion</td>
</tr>
</tbody>
</table>

Fig. 2. Apparatus for phantom cube tests.
stiffness measurements that are highly correlated to those found by voluntary contraction (Theis et al., 2012) and was judged to be acceptable to subjects with recent ruptures. The sequences had both AutoQual and MS methods applied. Due to lack of ground truth we report qualitative comments of the 2D tracking, average NCC over the region of interest as a matching quality metric and the standard deviation of strain as a noise descriptor.

5. Results

5.1. Rigid body motion phantom results

There were only small differences between the two methods in the errors of the steady state speeds for the range investigated (Fig. 3). Both algorithms overestimated the steady state speed for speeds of 1–2.5 mm/s and underestimated for the 3.5–5 mm/s tests.

5.2. Controlled strain phantom tests

The AutoQual method showed substantially lower NSE values at all strains (Fig. 4). The mean NSE for the AutoQual method was 0.00122 compared with the MS method NSE of 0.00241.

The variability of the calculated strain fields at different compression speeds is shown in Fig. 5. The AutoQual and MS methods have similar uniformity of strain field speeds up to 4.0 mm/s, but above this the MS method has less uniform strain fields than AutoQual.

5.3. In vivo data

Figs. 6 and 7 show a newly ruptured Achilles tendon subjected to passive ankle flexion by a few millimeters (subject A in Table 1). The B-mode image (Fig. 7, left) clearly shows a large, hypoechoic region which is at the rupture zone (h). There is a clear displacement gradient in both of the displacement images (Figs. 6 and 7, middle) where the part of the tendon closest to the calcaneus (the right side of this image) moves more than the rest.

The MS displacement image (Fig. 6, middle) shows the sources of some of the artifacts in the strain image (Fig. 6, right). Points p, q and r all show local areas of small discontinuities in the displacement field. This could be caused by relatively small errors at lower resolutions of the MS method being propagated to higher scales. The MS method is vulnerable to evaluating lateral displacements to discrete quantities, resulting in a defined edge rather than the steady gradient shown by the AutoQual method (Fig. 7, middle). Consequently, the AutoQual strain field (Fig. 7, right) is more uniform with a clear band of high strain across the blood clot boundary (h). The MS strain field is more confused, with alternating bands of negative and positive strains in all significant areas.

The AutoQual method consistently provides a higher NCC than the MS method (Table 2) and the lower standard deviation of the strain field in the area of interest shows that the AutoQual method provides more consistent lateral strain measurements (Table 3).

6. Discussion

Quantitative evaluation of strain is difficult to achieve in a rigorous and repeatable manner in vivo and evaluating the performance of the methods designed to estimate these quantities is equally challenging. Differing set ups between research groups from hardware, types of algorithm used or loading conditions can result in differences of interpretation.

Recent publications have been able to perform lateral tracking and local strain estimations on ex vivo tendons such as Chernak and Thelen (2012) and Korstanje et al. (2010) but the use of tissue alone for algorithm validation is not ideal. The possibility for variability in the tissue and gripping problems makes this difficult to achieve or repeat.

Korstanje et al. tracked rigid body motion and optimized the frame interval to minimize quantization error in their tracking algorithm. Their reported relative error range was −2.2% to 4.4% (relative displacement); ours is −1.6% to 2.3% (relative speed based on Fig. 3). We have more accurately described the dynamics of our algorithm at different speeds and can demonstrate our...
accuracy at speeds typical of slow passive motion of a tendon or muscle, although Korstanje et al. were able to track displacements at speeds of up to 16 mm/s. We have shown that rigid body tracking alone is, however, not a sensitive test, as both the MS and AutoQual methods showed similar accuracies. It is notable that both of our algorithms showed overestimation initially and then underestimation of the steady state speed (Fig. 3). We calculate that the speed for exactly 1 pixel/frame for our hardware is approximately 3.2 mm/s – this could indicate that we are experiencing an interpolation error that requires further investigation.

Chernak et al. only validated the displacement accuracy by commenting that the mid-section displacement of the ex vivo tendon is approximately a half of the grip-to-grip separation and that the average frame-to-frame displacements correlate well to a linear fit. Chernak et al. reported strains at the mid section of the tendon which varied considerably, making it difficult to judge if the experiment was capable of validating the strain measured by their lateral elastography method. Our phantom strain experiments have demonstrated similar values with three repetitions at each different speed and different strain quantities, allowing us to characterize the errors from the elastography methods.

The phantom strain experiment shows the improved performance of the AutoQual method over the MS method. The strain fields showed similar levels of smoothness and uniformity and with a notably lesser deviation at grip-to-grip speeds above 4.0 mm/s (Fig. 5). At these higher speeds it is more likely that the MS algorithm will be unable to find a good correlation, and may find a local NCC maximum far away from the true value. The AutoQual method’s QDS, ASR and ABS features mean that even with decorrelated data it is unlikely that a discontinuous displacement will be found but will retain flexibility. This leads to less noise in the displacement field which is more effectively regularized by median filtering. The NSE for a range of strains was also shown to be consistently lower (Fig. 4). This shows that the AutoQual method is consistently providing more accurate local lateral strain than the MS method.

The in vivo data showed displacement and strain images that were qualitatively improved by the AutoQual method. The displacement and strain fields can also cover a wider area due to the ABS capability. The edge noise from material leaving the field of view is also reduced with the AutoQual method. This additional field of view can aid the overall clinical perception. While the Autoqual method shows significant improvement on these in vivo sequences, errors can still occur due to out of plane motion from
the tissue motion, probe slip or loss of signal where the algorithm correctly tracks the image motion but that motion does not accurately represent the strains induced in the tissue.

Subject A shows areas of low signal, fast motion and material rotation, yet the AutoQual method provides visually credible results, a higher average NCC and a lower distribution of local strain values. The AutoQual block matching algorithm was more effective for subjects B, C and D also, despite slow motorized flexion leading to an improved performance of the MS method. In these scans the majority of the error in the MS evaluations could be tracked to a few frames (approximately one in ten frames) where these were either fast motion or an out of plane shift, leading to decorrelation. AutoQual was more able to cope with these factors and consistently lacked gross errors in the displacement field.

7. Conclusion

This paper has presented an innovative implementation of lateral ultrasound elastography in vivo for ruptured and partially healed Achilles tendons and simple, easily reproducible methods for testing such an algorithm. The innovations presented include the following:

- The first implementation of a Quality Determined Search algorithm for quantitative lateral elastography.
- The implementation of innovative Adaptive Block Size and Automatic Search Range concepts which compliment the QDS method and reduce the requirement to optimize search ranges.
- A simple, novel and repeatable experiment with a mechanical testing machine and a phantom block for quantifying rigid body lateral displacement error, lateral strain NSE and standard deviation.
- Demonstrating the AutoQual method is quantitatively superior to a multiscale method in the phantom block experiments.
- Demonstrating the AutoQual method is qualitatively superior than a multiscale method for four in vivo examples with passive dorsiflexion.

Further work will allow the simultaneous measurement of force while scanning a patient, enabling an estimate material properties of the tendon. We also intend to use this method on an existing dataset previously published to assess its utility in monitoring healing during a longitudinal clinical study (Brown et al., 2012). The improvements presented here are a step toward a developing a clinically useful method for assessing longitudinal mechanical properties of tendons and other tissues.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version of http://dx.doi.org/10.1016/j.jbiomech.2013.07.044.

References


Conflict of interest statement

None.

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