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# Achilles and patellar tendinopathy display opposite changes in elastic properties: A shear wave elastography study

B. Coombes, K. Tucker, B. Vicenzino, V. Vuvan, R. Mellor, L. Heales,  
Antoine Nordez, François Hug

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1 **Achilles and patellar tendinopathy display opposite changes in elasticity: An ultrasound**  
2 **shear wave elastography study.**

3 **Authors:**

4 Brooke Kaye Coombes (PhD)<sup>1</sup>; Kylie Tucker<sup>1</sup> (PhD); Bill Vicenzino (PhD)<sup>2</sup>; Viana Vuvan<sup>2</sup>;  
5 Rebecca Mellor<sup>2</sup>; Luke Heales (PhD)<sup>3</sup>; Antoine Nordez (PhD)<sup>4</sup>; François Hug (PhD)<sup>2,4,5</sup>

6  
7 **Author affiliations:**

8 <sup>1</sup>School of Biomedical Sciences, The University of Queensland, Brisbane Australia

9 <sup>2</sup>School of Health and Rehabilitation Sciences, The University of Queensland, Brisbane,  
10 Australia

11 <sup>3</sup>School of Human, Health and Social Science, Division of Physiotherapy, Central  
12 Queensland University, Rockhampton, Australia

13 <sup>4</sup>Faculty of Sport Sciences, Laboratory “Movement, Interactions, Performance” (EA 4334),  
14 University of Nantes, Nantes, France

15 <sup>5</sup>Institut Universitaire de France (IUF), Paris, France.

16

17 **Corresponding author:** Dr Brooke Coombes

18 University of Queensland, School of Biomedical Sciences, Otto Hirschfeld Bld 81, St Lucia  
19 4072

20 P: +614 3750 4508 E: [b.coombes@uq.edu.au](mailto:b.coombes@uq.edu.au)

21

22 **Running Head:** Tendinopathy: A shearwave elastography study

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34

35 ABSTRACT

36 Purpose: To compare tendon mechanical properties (elastic modulus) and structural  
37 properties (thickness) of healthy individuals with those with Achilles or patellar  
38 tendinopathy.

39 Methods: Sixty-seven participants (22 Achilles tendinopathy, 17 patellar tendinopathy, 28  
40 healthy controls) were recruited between March 2015-March 2016. Shear wave velocity  
41 (SWV), an index of tissue elasticity, and tendon thickness were measured bilaterally at mid-  
42 tendon and insertional regions of Achilles and patellar tendons by an examiner blinded to  
43 group. Analysis of covariance, adjusted for age, body mass index and sex was used to  
44 compare differences in tendon thickness and SWV between the two tendinopathy groups  
45 (relative to controls) and regions. Tendon thickness was included as a covariate for analysis  
46 of SWV.

47 Results: Compared to controls, participants with Achilles tendinopathy had lower SWV at the  
48 distal insertion (Mean difference MD; 95% CI: -1.56; -2.49 to -0.62 m/s;  $P<0.001$ ), and  
49 greater thickness at the mid-tendon (MD 0.19; 0.05 to 0.33 cm;  $P=0.007$ ). Compared to  
50 controls, participants with patellar tendinopathy had higher SWV at both regions (MD 1.25;  
51 0.40 to 2.10 m/s;  $P=0.005$ ), and greater thickness proximally (MD 0.17; 0.06 to 0.29 cm;  
52  $P=0.003$ ).

53 Conclusion: Compared to controls, participants with Achilles and patellar tendinopathy  
54 displayed lower Achilles tendon elasticity and higher patellar tendon elasticity respectively.  
55 More research is needed to explore whether maturation, aging or chronic load underlie these  
56 findings and whether current management programs for Achilles and patellar tendinopathy  
57 need to be tailored to the tendon.

58

59 Key words: jumper's knee; Aixplorer; ultrasound, elasticity, stiffness, musculoskeletal,

60 rehabilitation, pain

61

62 INTRODUCTION

63 Painful disorders of the Achilles and patellar tendons are a major problem in competitive and  
64 recreational sports as well as the sedentary population. More than half (52%) of elite runners  
65 develop Achilles tendinopathy during their lifetime,<sup>1</sup> while the prevalence of current or  
66 previous patellar tendinopathy in volleyball or basketball athletes is similar (50-55%).<sup>2</sup>  
67 Ultrasonography is widely used for diagnosis of tendinopathy, however classical ultrasound  
68 findings show limited correlation with symptoms<sup>3,4</sup> and lack fundamental information on  
69 tissue mechanical properties.

70

71 Shear wave elastography is a relatively new ultrasound imaging technique that allows non-  
72 invasive estimation of soft-tissue viscoelastic properties in vivo by measurement of Shear  
73 Wave Velocity (SWV) (in meters per second) generated by the ultrasound pulse.<sup>5</sup>  
74 Importantly, as the SWV may be determined from a relatively small region of tissue (as  
75 opposed to the whole structure) it can provide direct measurement of specific regions of  
76 interest within tendon,<sup>6,7</sup> which is important because discrete areas of pathology are reported  
77 in people with tendinopathy.<sup>8</sup>

78

79 Using this technique, lower elasticity was demonstrated in patients with Achilles  
80 tendinopathy,<sup>9,10</sup> whereas both higher<sup>11</sup> and lower<sup>10</sup> elasticity were reported in separate  
81 studies of patients with patellar tendinopathy. By estimating patellar tendon stiffness from the  
82 relationship between the force applied to the tendon and its associated proximal insertion  
83 displacement assessed through B-mode ultrasound, inconsistent findings are also reported (no  
84 change<sup>12</sup> or decreased<sup>8</sup> stiffness). However, this indirect method to assess tendon stiffness has  
85 two major drawbacks: i) the tendon force is indirectly estimated (as the force is applied  
86 externally to a body segment, rather than directly on the tendon), and ii) only global

87 properties of the whole tendon can be estimated. This is surprising given the similar  
88 histological appearance in patellar and Achilles tendinopathy,<sup>13</sup> but other factors, including  
89 age, body composition and training might also modulate the mechanical properties of  
90 tendon.<sup>14</sup> For example, athletes with patellar tendinopathy are significantly younger (mean  
91 age  $23 \pm 3$  years), taller (mean height  $185 \pm 10$  cm) and heavier (mean weight  $77 \pm 11$  kg),  
92 although of similar body mass index (BMI) (mean BMI  $23 \pm 2$  kg/m<sup>2</sup>) than those without  
93 symptoms.<sup>15</sup> In comparison, participants with Achilles tendinopathy are older (mean age  $53 \pm$   
94  $12$  years) and have higher BMI (mean  $35 \pm 8$  kg/m<sup>2</sup>) than control participants.<sup>16</sup>

95  
96 Methodological differences surrounding measurement of tendon properties may also  
97 contribute to the variability between studies.<sup>17</sup> Of relevance to the shear wave elastography  
98 technique for tendons, shear wavelengths can be greater than tendon thickness, leading to  
99 guided wave propagation.<sup>18</sup> Within this context, the relationship between group velocity of  
100 the shear wave estimated by commercialized ultrasound shear wave elastography techniques  
101 and tendon elasticity is affected by tendon thickness. Thus, information about both SWV and  
102 thickness must be sought to interpret changes in SWV as changes in elasticity. In addition,  
103 some authors<sup>9</sup> have reported measurement artefacts during shear wave elastography  
104 acquisition, including signal void areas within an elastogram. While their presence has been  
105 suggested to be a potential marker of intratendinous damage,<sup>9</sup> comprehensive evaluation of  
106 its presence is lacking.

107  
108 The purpose of our study was to determine whether tendon elasticity and thickness of healthy  
109 individuals differ from those with Achilles or patellar tendinopathy using shear wave  
110 elastography. We proposed that regional differences in SWV and thickness would be present  
111 in those with tendinopathy compared to controls. As other factors may also modulate the

112 elastic properties of connective tissues, we also investigated the relationship between SWV  
113 and age, sex and BMI. Last, we aimed to quantify elastography signal void in tendinopathic  
114 and healthy tendon.

115

## 116 MATERIALS AND METHODS

117 Participants with or without tendinopathy were consecutively recruited by social media and  
118 local advertisement between March 2015 and March 2016. Inquiries were directed to an  
119 online screening questionnaire and eligible participants were invited to attend physical  
120 screening by a musculoskeletal physiotherapist not involved in testing. The inclusion criteria  
121 for patients with tendinopathy were self-reported tendon pain over the Achilles or patellar  
122 tendon of at least 20 on a 0-100 numerical rating scale (NRS), and of duration 12 weeks or  
123 more. Physical examination confirmed tendon pain on palpation and loading (by calf raise or  
124 decline squat). The number of single leg calf raises or decline squats performed before pain  
125 onset was recorded. Exclusion criteria were corticosteroid injection (in previous 6 months),  
126 local surgery or other specific pathology (e.g., fracture, diabetes, inflammatory, systemic or  
127 neurological disease, malignancy, radiculopathy). All participants were excluded if they had  
128 experienced back or other leg symptoms requiring treatment or limiting work/sport in the  
129 previous six months. This study was approved by the University of Queensland Medical  
130 Research Ethics Committee and all participants provided written informed consent.

131

132 Participants with tendinopathy completed either the Achilles<sup>19</sup> or Patellar<sup>20</sup> versions of the  
133 Victorian Institute of Sport Assessment (VISA), to provide validated information about pain  
134 and disability for their (most) affected leg. Total scores range from 0 to 100, 100 representing  
135 an asymptomatic, fully performing individual. In addition to basic demographic information  
136 (age, sex, height and weight), all participants completed the Active Australia Questionnaire,



137 to measure physical activity during the preceding week.<sup>21</sup> Total activity time (minutes) was  
138 calculated by adding the time spent in walking and moderate activity and twice the time spent  
139 in vigorous activity.

140

141 *Elastography acquisition* Upon arrival participants rested in lying for five minutes prior to  
142 examination using the supersonic shear imaging technique (Aixplorer version 8.2, Supersonic  
143 Imagine, Aix-en-Provence, France) with 50 mm linear transducer (15-4MHz). A single  
144 operator (BKC) performed all scans to eliminate inter-observer variability.<sup>22</sup> Interday  
145 reliability was examined by testing both legs in six healthy participants on two occasions  
146 separated by 48 hours. Intraclass correlation coefficients (ICC) ranged from 0.71 to 0.80 for  
147 measurement of SWV and 0.78 to 0.97 for thickness measurements (Table 1).

148

149 Examination was performed blind to the physical examination and group by scanning  
150 bilateral patellar and Achilles tendons in a randomised order for all participants. For Achilles  
151 measurements, participants lay in prone with their leg extended and ankle resting over the  
152 edge of the plinth. The participant's resting ankle angle was measured using a hand-held  
153 goniometer. For patellar tendon measurement, participants lay in supine, supported in 30°  
154 knee flexion and neutral hip rotation. Based on previous report of the slack angle of the  
155 Achilles tendon ( $43.7 \pm 3.2^\circ$  plantarflexion)<sup>23</sup> and unpublished observations of the patellar  
156 tendon, both positions were assumed to have some passive tension on the respective tendons.  
157 The amount of signal void within each ROI, defined as the percentage of all pixels without  
158 elastography colour was also calculated. For SWV measurement, we made sure that regions  
159 with signal void were not confused with a low value. Participants were told to remain  
160 completely relaxed during testing.

161

162 The ultrasound transducer head was aligned in the longitudinal plane with collagen fibres,  
163 applying minimal pressure.<sup>24</sup> Tendon thickness was measured from longitudinal B-mode  
164 images using the inbuilt Aixplorer distance function. For the Achilles tendon, the maximum  
165 perpendicular distance between anterior and posterior tendon boundaries was measured over  
166 the free tendon (2-4 cm proximal to the Achilles insertion) and immediately proximal to the  
167 calcaneal attachment. For the patellar tendon, the maximum perpendicular distance  
168 immediately distal to the apex of the patellar and at the midpoint between patellar and tibial  
169 attachments was measured. Using the shear wave elastography mode (penetration;  
170 persistence low; smoothing 5), the transducer was held for ~10 s duration, and two or three  
171 measurements were repeated in each location. For the Achilles tendon, separate images were  
172 collected for measurement of mid-tendon and insertional regions, while both patellar regions  
173 could be visualised without moving the transducer.

174

175 *Data extraction* Elastography clips (10 s duration, sampling rate of 1.5-1.8 Hz) were  
176 converted into PNG images (~20-26 images), then processed offline using customised Matlab  
177 scripts (R2016a, The Mathworks, Natick, MA, USA) by a research assistant who was blinded  
178 to group. The following regions of interest (ROI) were manually traced on the adjacent B-  
179 mode image keeping within the peritendinous boundary: For the Achilles tendon, ROI were  
180 measured at the free tendon (ROI length ~3 cm) and immediately proximal to the calcaneal  
181 attachment (ROI length ~1 cm). For the patellar tendon, ROI were measured mid-way  
182 between proximal and distal attachments (ROI length ~2 cm) and 0.5 cm from the apex of the  
183 patella (ROI length ~0.5 cm). The mean SWV (m/s) was averaged over the ROIs of  
184 consecutive images. The amount of signal void within each ROI, defined as the percentage of  
185 all pixels without elastography colour, was also calculated. For SWV measurement, the  
186 Matlab script ensured that regions with signal void were not confused with a low value.

187 Examples of Achilles and patellar elastograms (highlighting signal void) are provided in  
188 Figure 1 and Figure 2, respectively.

189

190 *Statistical analysis* For Achilles tendinopathy (AT) and patellar tendinopathy (PT) groups,  
191 only the affected leg or self-reported worst leg (in bilateral cases) was included in analysis.  
192 For healthy control (HC) participants, we randomly matched Achilles and patellar tendons to  
193 ensure an equivalent proportion of left/right legs in the analysed sample, as recommended by  
194 previous studies.<sup>25</sup> Repeated measures ANCOVAs were used to compare tendon SWV and  
195 thickness between groups (AT vs HC or PT vs HC) and regions (mid-tendon vs insertion).  
196 Where significant group-by-region interaction was observed, generalised linear models  
197 (GLM) were used to estimate mean differences (MD) and 95% confidence intervals (CI)  
198 between groups for each tendon region. Age, BMI and sex were included as covariates in all  
199 models. In addition, we included tendon thickness as a covariate in analyses of SWV, based  
200 on evidence that tendon thickness may affect SWV.<sup>18,26</sup> We dichotomised signal void as  
201 present if it affected more than 5% of pixels within the ROI and differences between groups  
202 were compared using Pearson Chi-square statistic.

203

204 Receiver operating characteristic (ROC) analysis was performed to determine the threshold,  
205 specificity and sensitivity to differentiate HC from AT or PT, using the Youden's index to  
206 identify the cut-point.<sup>27</sup> Finally, Pearson correlations were computed to identify relationships  
207 between SWV and demographic or injury factors (the latter for tendinopathy groups only).  
208 Statistical analysis was performed using SPSS (22.0 IBM Corp). Significance was set at  
209  $P < 0.05$ .

210

211 RESULTS

212 *Participants* Sixty-seven adults (22 with AT, 17 with PT and 28 HC who were free of tendon  
213 pain) were recruited. Demographic and injury information is summarised in Table 2 and  
214 reasons for participant exclusion are listed in Supplemental Figure 1. Participants with AT  
215 were significantly older than those with PT ( $P<0.001$ ) and had higher BMI than HC  
216 ( $P<0.001$ ). Total activity time was not statistically different between the three groups  
217 ( $P=0.343$ ). Similar symptom duration ( $P=0.943$ ) and pain/disability levels ( $P=0.781$ ) were  
218 found for AT and PT groups. The resting ankle angle adopted during Achilles tendon testing  
219 was not different between groups (mean plantarflexion angle  $24.3\pm 5.0^\circ$ ).

220

221 *Achilles tendinopathy* Compared to HC, participants with AT had greater thickness at the  
222 mid-Achilles (MD 95% CI: 0.19; 0.05 to 0.33 cm;  $P=0.007$ ), but not at the Achilles insertion  
223 ( $P=0.80$ ) (group-by-region interaction,  $P=0.035$ , Figure 3a). Compared to HC, participants  
224 with AT had lower SWV at the Achilles insertion (MD -1.56; -2.49 to -0.62 m/s;  $P<0.001$ ),  
225 but not mid-tendon region ( $P=0.456$ ) (group-by-region interaction,  $P<0.001$ , Figure 3c).  
226 Signal void of more than 5% of the ROI was present in four HC (8.9%) and 10 AT (45.5%)  
227 cases (Pearson Chi-square  $P=0.001$ ).

228

229 Using ROC analysis, mid-Achilles thickness above 0.64 cm, SWV below 9.7 m/s and signal  
230 void above 1.5% of the ROI were identified as cut-points to differentiate HC and AT (Table  
231 3). Lower Achilles SWV was associated with higher age ( $r=-0.49$ ,  $P<0.001$ ), greater BMI  
232 ( $r=-0.53$ ,  $p<0.001$ ), greater pain and disability as measured by VISA-A ( $r=0.49$ ,  $P=0.046$ ) and  
233 fewer single leg calf raises before pain onset ( $r=0.646$ ,  $P=0.001$ ).

234

235 *Patellar tendinopathy* Compared to HC, participants with PT had greater thickness at the  
236 proximal patellar (MD 0.17; 0.06 to 0.29 cm;  $P=0.003$ ), but not mid-patellar ( $P=0.31$ ) region

237 (group-by-region interaction,  $P=0.01$ , Figure 3b). Compared to HC, participants with PT had  
238 higher SWV of the patellar tendon at both regions (MD 1.25; 0.40 to 2.10 m/s;  $P=0.005$ ,  
239 Figure 3d). Signal void of more than 5% of the ROI was present in 0 HC and 3 PT (17%)  
240 cases (Pearson Chi-square  $P=0.021$ ).

241

242 Using ROC analysis, proximal patellar thickness above 0.62 cm, SWV above 6.9 m/s and  
243 signal void above 0.7% of the ROI were identified cut-points to differentiate HC and PT  
244 (Table 3). Lower proximal patellar SWV was correlated with age ( $r=-0.368$ ,  $P=0.013$ ) only.

245

## 246 DISCUSSION

247 Using the non-invasive ultrasound-based technique of shear wave elastography, we observed  
248 lower insertional Achilles tendon elasticity and higher patellar tendon elasticity in  
249 participants with tendinopathy relative to healthy controls. Lower elasticity in Achilles  
250 tendinopathy is consistent with two recent studies using shear wave elastography,<sup>9, 10</sup> and  
251 other force-deformation methods.<sup>28</sup> However, evidence for changes in patellar tendon  
252 mechanical properties in tendinopathy varies between methods<sup>8, 29</sup> and studies.<sup>10, 11</sup> Using  
253 shear wave elastography, Zhang (2014) found significantly greater elasticity and thickness for  
254 the proximal patellar tendon in 13 athletes with unilateral PT, compared to both the  
255 unaffected tendon and healthy control participants.<sup>11</sup> In contrast, Dirrichs et al (2016)  
256 reported lower elasticity in symptomatic compared to asymptomatic tendons in 38  
257 participants with patellar tendinopathy.<sup>10</sup> However, Dirrichs et al (2016) reported using a  
258 much smaller ROI (standardised size of 1 mm) placed in the stiffest area of tendon.<sup>10</sup>

259

260 Although causal relationships cannot be inferred from this cross-sectional study, it is possible  
261 that different pathobiological processes associated with maturation and aging may be at play

262 in patellar and Achilles tendinopathy, respectively. Animal work demonstrates that  
263 maturation and aging have different influences on the physical, chemical and mechanical  
264 properties of tendon.<sup>30</sup> In their experimental study in rats, Vogel et al (1980) observed a sharp  
265 rise in elasticity during maturation and a smaller but significant decrease during aging.<sup>30</sup>  
266 These changes in mechanical parameters were closely related to cross-linking of collagen.  
267 Significant increases in tendon elasticity with maturation<sup>31</sup> may explain why adolescent  
268 athletes have three times greater odds of patellar than Achilles tendinopathy.<sup>32</sup> In our study,  
269 older age was associated with lower Achilles tendon elasticity, which is in agreement with  
270 previous investigations using shear wave elastography,<sup>7, 24</sup> and other methods.<sup>33</sup> Differences  
271 in chronic load may alternatively contribute to our findings. Cassel et al (2015) reported that  
272 athletes with patellar tendinopathy were taller and heavier and performed higher training  
273 volumes than athletes without patellar tendinopathy,<sup>32</sup> attributes which may induce adaptation  
274 by increased tendon elasticity. Conversely, sedentary lifestyles adopted by some people with  
275 Achilles tendinopathy may contribute to lower elasticity. Interestingly, biomechanical studies  
276 demonstrate that the effects of stress deprivation on connective tissue are more prolonged at  
277 the insertion than mid-tissue region,<sup>34</sup> potentially explaining the significant reduction of  
278 mechanical properties at the Achilles insertion. Of clinical importance, Achilles tendon  
279 elasticity was significantly correlated with self-reported pain and disability over the  
280 preceding week and with a rudimentary measure of the loading capacity of the Achilles  
281 tendon.

282

283 The strengths of this study include the blinded design and concurrent investigation of two  
284 different lower limb tendinopathies. We acknowledge that interpretation of differences in  
285 SWV as differences in elasticity is not straightforward, as larger tendon thickness can lead to  
286 a higher SWV due to the effects of guided wave propagation, independent of any change in

287 actual tissue elasticity.<sup>18, 35</sup> In the present study, no between-group difference in thickness  
288 was observed for the mid-patellar tendon and the Achilles tendon insertion, increasing our  
289 confidence in our interpretations that mechanical properties were altered. However, it is  
290 possible the technique failed to detect a less stiff (but thicker) mid-Achilles tendon. This  
291 study extends upon previous ones by quantifying signal void within the measured ROI.  
292 Signal void was highly specific (82-96%) to cases with tendinopathy. Although currently  
293 speculative, its presence may be due to intra-tendinous swelling or tears,<sup>9</sup> greater attenuation  
294 of shear waves as a result of altered viscosity,<sup>26</sup> or severe matrix disruption and increased  
295 anisotropy.<sup>36</sup> Further studies are needed to determine the impact of attenuation on SWV in  
296 the considered region, and relate signal void to changes in matrix proteoglycan concentration  
297 due to tendinopathy.

298

299 Limitations of the current study include the moderate reliability estimates, small sample size  
300 and heterogenous tendinopathy population, which included participants with symptoms at  
301 either mid-tendon or insertional regions. We chose to recruit both male and female control  
302 participants with a range of ages, rather than individually match participants on the basis of  
303 age or sex. Although not without limitation, statistical adjustment by including age, sex and  
304 BMI as covariates in all models, was performed in an attempt to explore which factors  
305 modulate changes in tendon properties. Other potential confounding factors such as sporting  
306 history and muscle strength were not measured.

307

308 In summary, in the positions tested here, Achilles tendon SWV less than 9.7 m/s and patellar  
309 tendon SWV more than 6.9 m/s showed high specificity (81% and 82% respectively) and  
310 sensitivity (79% and 77%) for detecting Achilles and patellar tendinopathy respectively,

311 suggesting this method may have important clinical utility for early detection of patients at  
312 risk of tendon pathology.

313

314 PERSPECTIVE

315 Achilles and patellar tendinopathy share similar histopathology, but affect different age  
316 groups. The present study suggests that the two lower limb tendinopathies display different  
317 mechanical properties when compared to tendons from healthy individuals. More research is  
318 needed to explore whether maturation, aging or chronic load underlie these findings and  
319 whether current management programs for Achilles and patellar tendinopathy need to be  
320 tailored to the tendon.



321 Table 1: Inter-day reliability (48 hour interval) for measurement of tendon thickness and  
 322 shear wave velocity in six healthy individuals. ICC: Intraclass correlation coefficient.  
 323

Tendon region	Session 1 mean (SD)	Session 2 mean (SD)	ICC (95%CI)
Mid-Achilles	0.54 (0.22)	0.57 (0.22)	0.97 (0.92, 0.99)
Insertional Achilles	0.40 (0.08)	0.41 (0.06)	0.78 (0.47, 0.92)
Mid-patellar	0.34 (0.05)	0.34 (0.06)	0.84 (0.59, 0.94)
Proximal patellar	0.53 (0.07)	0.53 (0.07)	0.82 (0.56, 0.94)
	<b>Shear wave velocity (m/s)</b>		
Mid-Achilles	10.4 (1.1)	10.8 (0.8)	0.71 (0.24, 0.91)
Insertional Achilles	9.8 (1.6)	10.0 (1.2)	0.69 (0.11, 0.92)
Mid-patellar	6.1 (0.8)	6.0 (0.7)	0.71 (0.22, 0.91)
Proximal patellar	6.4 (1.2)	6.4 (1.2)	0.80 (0.42, 0.94)

324

325

326 Table 2: Demographic and injury characteristics for Healthy Control, Patellar tendinopathy  
 327 and Achilles tendinopathy cohorts.

	<b>Healthy Control</b>	<b>Patellar Tendinopathy</b>	<b>Achilles Tendinopathy</b>
n	28	17	22
<b><i>Demographic information</i></b>			
Age (years)	38.3 (16.7)	29.4 (6.6)	47.5 (11.4)*
BMI (kg/m <sup>2</sup> )	22.8 (2.7)	25.4 (3.3)	28.1 (5.3)*
Female sex n (%)	17 (61%)	4 (24%)*	9 (41%)
Total activity time (mins)	582.2 (451.9)	797.9 (481.3)	642.4 (491.3)
<b><i>Injury information</i></b>			
Injury duration (years)		3.8 (3.4)	3.7 (6.9)
VISA-A or VISA-P (0-100)		57.1 (14.4)	58.6 (16.5)
Worst pain (NRS, 0-10)		5.2 (2.3)	6.0 (2.1)
Average pain (NRS, 0-10)		3.4 (2.1)	4.2 (1.9)
Resting pain (NRS, 0-10)		1.2 (2.4)	1.4 (1.5)
Calf raises (repetitions to pain onset)		NA	9.7 (8.6)
Decline squats (repetitions to pain onset)		2.1 (1.7)	NA
<b><i>Symptom distribution n (%)</i></b>			
Bilateral tendinopathy		9 (53%)	14 (64%)
Proximal: distal symptoms		15 (88%): 2 (12%)	NA
Mid-tendon: insertional symptoms		NA	19 (87%): 9 (41%)

328  
 329 Data represents mean (SD) unless otherwise specified. \* Significant (p<0.05) differences  
 330 compared to healthy controls.

331

332 Table 3: Results of Receiver Operating Characteristic analysis.

	<b>Mean Threshold</b>	<b>Specificit y</b>	<b>Sensitivit y</b>
<b>Thickness</b>			
Mid-Achilles	≥ 0.64 cm	89.3 %	72.7 %
Insertional Achilles	≥ 0.44 cm	67.9 %	59.1 %
Proximal patellar	≥ 0.62 cm	100.0 %	58.8 %
Mid-Patellar	≥ 0.33 cm	50.0 %	82.4 %
<b>Shear wave velocity</b>			
Mid-Achilles	≤ 6.80 m/s	68.2 %	75.0 %
Insertional Achilles	≤ 9.68 m/s	81.0 %	78.6 %
Proximal patellar	≥ 6.90 m/s	82.1 %	76.5 %
Mid-Patellar	≥ 7.03 m/s	92.9 %	35.3 %
<b>Signal void</b>			
Mid-Achilles	≥ 1.5 %	82.1 %	59.1 %
Insertional Achilles	≥ 5.1 %	96.4 %	38.1 %
Proximal patellar	≥ 0.7 %	96.4 %	41.2 %
Mid-Patellar	≥ 0.5 %	82.1 %	41.2 %

333

334 Thresholds for tendon thickness (in cm), shear wave velocity (in m/s) and signal void (as a

335 percentage of total ROI) to differentiate healthy and tendinopathic tendon have been

336 calculated using the Youden's index. Specificity and sensitivity were generated at these cut-

337 points.

338

339 Figure 1: Example shear wave elastograms of the Achilles tendon from healthy control (1a)  
340 and Achilles tendinopathy participants (1b and 1c). Signal void highlighted (asterisk) in 1c.

341

342 Figure 2: Shear wave elastograms of the patellar tendon from healthy control (1a) and  
343 Achilles tendinopathy participants (1b and 1c). Signal void highlighted (asterisk) in 2c.

344

345 Figure 3: Thickness and Shear wave velocity (SWV) of the Achilles tendon (a and c) and  
346 patellar tendons (b and d) for Healthy Control (Blue), Achilles tendinopathy (Red) and  
347 patellar tendinopathy (orange). Values represent mean and SD. \*Significant ( $P < 0.05$ )

348 differences between tendinopathy and healthy control groups (determined by Generalised  
349 linear model adjusted for age, body mass index, sex and thickness (for SWV measures).

350

351

352 Supplemental Content Figure 1: Recruitment numbers and participant eligibility information

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356 References:

- 357 1. Kujala UM, Sarna S, Kaprio J (2005) Cumulative incidence of achilles tendon  
358 rupture and tendinopathy in male former elite athletes. Clin J Sport Med.15:133
- 359 2. Lian OB, Engebretsen L, Bahr R (2005) Prevalence of jumper's knee among  
360 elite athletes from different sports: a cross-sectional study. Am J Sports Med.33:561
- 361 3. Cook JL, Khan KM, Kiss ZS, Coleman BD, Griffiths L (2001) Asymptomatic  
362 hypoechoic regions on patellar tendon ultrasound: A 4-year clinical and ultrasound  
363 followup of 46 tendons. Scand J Med Sci Sports.11:321
- 364 4. Emerson C, Morrissey D, Perry M, Jalan R (2010) Ultrasonographically  
365 detected changes in Achilles tendons and self reported symptoms in elite gymnasts  
366 compared with controls--an observational study. Man Ther.15:37
- 367 5. Bercoff J, Tanter M, Fink M (2004) Supersonic shear imaging: a new  
368 technique for soft tissue elasticity mapping. IEEE transactions on ultrasonics,  
369 ferroelectrics, and frequency control.51:396
- 370 6. Dewall RJ, Jiang J, Wilson JJ, Lee KS (2014) Visualizing tendon elasticity in  
371 an ex vivo partial tear model. Ultrasound Med Biol.40:158
- 372 7. Slane LC, Martin J, DeWall R, Thelen D, Lee K (2016) Quantitative ultrasound  
373 mapping of regional variations in shear wave speeds of the aging Achilles tendon.  
374 Eur Radiol.
- 375 8. Helland C, Bojsen-Moller J, Raastad T, Seynnes OR, Moltubakk MM,  
376 Jakobsen V, Visnes H, Bahr R (2013) Mechanical properties of the patellar tendon in  
377 elite volleyball players with and without patellar tendinopathy. Br J Sports  
378 Med.47:862

- 379 9. Aubry S, Nueffer JP, Tanter M, Becce F, Vidal C, Michel F (2015)  
380 Viscoelasticity in Achilles tendonopathy: quantitative assessment by using real-time  
381 shear-wave elastography. *Radiology*.274:821
- 382 10. Dirrichs T, Quack V, Gatz M, Tingart M, Kuhl CK, Schradling S (2016) Shear  
383 Wave Elastography (SWE) for the Evaluation of Patients with Tendinopathies. *Acad*  
384 *Radiol*.
- 385 11. Zhang ZJ, Ng GY, Lee WC, Fu SN (2014) Changes in morphological and  
386 elastic properties of patellar tendon in athletes with unilateral patellar tendinopathy  
387 and their relationships with pain and functional disability. *PLoS ONE*.9:e108337
- 388 12. Kongsgaard M, Qvortrup K, Larsen J, Aagaard P, Doessing S, Hansen P,  
389 Kjaer M, Magnusson SP (2010) Fibril morphology and tendon mechanical properties  
390 in patellar tendinopathy: effects of heavy slow resistance training. *Am J Sports*  
391 *Med*.38:749
- 392 13. Maffulli N, Testa V, Capasso G, Ewen SW, Sullo A, Benazzo F, King JB  
393 (2004) Similar histopathological picture in males with Achilles and patellar  
394 tendinopathy. *Med Sci Sports Exerc*.36:1470
- 395 14. Bohm S, Mersmann F, Arampatzis A (2015) Human tendon adaptation in  
396 response to mechanical loading: A systematic review and meta-analysis of exercise  
397 intervention studies on healthy adults. *Sports Med*.1
- 398 15. Zwerver J, Bredeweg SW, van den Akker-Scheek I (2011) Prevalence of  
399 Jumper's knee among nonelite athletes from different sports: a cross-sectional  
400 survey. *Am J Sports Med*.39:1984
- 401 16. Scott RT, Hyer CF, Granata A (2013) The correlation of Achilles tendinopathy  
402 and body mass index. *Foot Ankle Spec*.6:283

- 403 17. Seynnes OR, Bojsen-Moller J, Albracht K, Arndt A, Cronin NJ, Finni T,  
404 Magnusson SP (2015) Ultrasound-based testing of tendon mechanical properties: a  
405 critical evaluation. *Journal of applied physiology* (Bethesda, Md : 1985).118:133
- 406 18. Helfenstein-Didier C, Andrade RJ, Brum J, Hug F, Tanter M, Nordez A,  
407 Gennisson JL (2016) In vivo quantification of the shear modulus of the human  
408 Achilles tendon during passive loading using shear wave dispersion analysis. *Phys*  
409 *Med Biol.*61:2485
- 410 19. Robinson JM, Cook JL, Purdam C, Visentini PJ, Ross J, Maffulli N, Taunton  
411 JE, Khan KM, Victorian Institute Of Sport Tendon Study G (2001) The VISA-A  
412 questionnaire: a valid and reliable index of the clinical severity of Achilles  
413 tendinopathy. *Br J Sports Med.*35:335
- 414 20. Visentini PJ, Khan KM, Cook JL, Kiss ZS, Harcourt PR, Wark JD (1998) The  
415 VISA score: an index of severity of symptoms in patients with jumper's knee (patellar  
416 tendinosis). Victorian Institute of Sport Tendon Study Group. *J Sci Med Sport.*1:22
- 417 21. Australian Institute of Health and Welfare. The Active Australia Survey: A  
418 guide and manual for implementation, analysis and reporting. Canberra2003.
- 419 22. Peltz CD, Haladik JA, Divine G, Siegal D, van Holsbeeck M, Bey MJ (2013)  
420 ShearWave elastography: repeatability for measurement of tendon stiffness. *Skeletal*  
421 *Radiol.*42:1151
- 422 23. Hug F, Lacourpaille L, Maisetti O, Nordez A (2013) Slack length of  
423 gastrocnemius medialis and Achilles tendon occurs at different ankle angles. *J*  
424 *Biomech.*46:2534
- 425 24. Aubry S, Risson JR, Kastler A, Barbier-Brion B, Siliman G, Runge M, Kastler  
426 B (2013) Biomechanical properties of the calcaneal tendon in vivo assessed by  
427 transient shear wave elastography. *Skeletal Radiol.*42:1143



- 428 25. Bohm S, Mersmann F, Marzilger R, Schroll A, Arampatzis A (2015)  
429 Asymmetry of Achilles tendon mechanical and morphological properties between  
430 both legs. *Scand J Med Sci Sports*.25:e124
- 431 26. Brum J, Bernal M, Gennisson JL, Tanter M (2014) In vivo evaluation of the  
432 elastic anisotropy of the human Achilles tendon using shear wave dispersion  
433 analysis. *Phys Med Biol*.59:505
- 434 27. Akobeng AK (2007) Understanding diagnostic tests 3: Receiver operating  
435 characteristic curves. *Acta Paediatr*.96:644
- 436 28. Arya S, Kulig K (2010) Tendinopathy alters mechanical and material  
437 properties of the Achilles tendon. *Journal of applied physiology (Bethesda, Md :*  
438 *1985)*.108:670
- 439 29. Coupe C, Kongsgaard M, Aagaard P, Vinther A, Boesen M, Kjaer M,  
440 Magnusson SP (2013) Differences in tendon properties in elite badminton players  
441 with or without patellar tendinopathy. *Scand J Med Sci Sports*.23:e89
- 442 30. Vogel HG (1980) Influence of maturation and aging on mechanical and  
443 biochemical properties of connective tissue in rats. *Mech Ageing Dev*.14:283
- 444 31. O'Brien TD, Reeves ND, Baltzopoulos V, Jones DA, Maganaris CN (2010)  
445 Mechanical properties of the patellar tendon in adults and children. *J*  
446 *Biomech*.43:1190
- 447 32. Cassel M, Baur H, Hirschmuller A, Carlsohn A, Frohlich K, Mayer F (2015)  
448 Prevalence of Achilles and patellar tendinopathy and their association to  
449 intratendinous changes in adolescent athletes. *Scand J Med Sci Sports*.25:e310
- 450 33. Onambele GL, Narici MV, Maganaris CN (2006) Calf muscle-tendon  
451 properties and postural balance in old age. *Journal of applied physiology (Bethesda,*  
452 *Md : 1985)*.100:2048

- 453 34. Woo SL, Gomez MA, Sites TJ, Newton PO, Orlando CA, Akeson WH (1987)  
454 The biomechanical and morphological changes in the medial collateral ligament of  
455 the rabbit after immobilization and remobilization. *J Bone Joint Surg Am.*69:1200
- 456 35. Mo J, Xu H, Qiang B, Giambini H, Kinnick R, An KN, Chen S, Luo Z (2016)  
457 Bias of shear wave elasticity measurements in thin layer samples and a simple  
458 correction strategy. *Springerplus.*5:1341
- 459 36. Neviasser A, Andarawis-Puri N, Flatow E (2012) Basic mechanisms of tendon  
460 fatigue damage. *J Shoulder Elbow Surg.*21:158
- 461