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Tensile and shear loading stability of all-inside meniscal repairs: an in vitro biomechanical evaluation

Brucker, P U ; Favre, P ; Puskas, G J ; von Campe, A ; Meyer, D C ; Koch, P P

Abstract: **BACKGROUND:** Most biomechanical studies for evaluation of the structural properties of meniscal repairs have been performed in tensile loading scenarios perpendicular to the circumferential meniscal fibers. However, meniscal repair constructs are also exposed to shear forces parallel to the circumferential meniscal fibers during healing, particularly in the midportion of the meniscus. **HYPOTHESIS:** Material properties of meniscal repair devices cannot be extrapolated from tensile to shear load scenarios. **STUDY DESIGN:** Controlled laboratory study. **METHODS:** In 84 harvested and isolated bovine lateral menisci following removal of adjacent soft tissue, a standardized vertical lesion was set followed by repair using all-inside flexible (FasT-Fix, FasT-Fix AB, RapidLoc) and rigid (Meniscus Screw, Meniscus Arrow) meniscal repair devices. Vertical and horizontal 2.0 Ethibond sutures were used as controls. The repaired meniscal construct was tested in a tensile (parallel to the axis of the tested repair device) and shear load scenario (perpendicular to the axis of the tested repair device) at 5 mm/min and 37 degrees C environmental temperature. Maximum load to failure, stiffness, and failure mode were recorded. **RESULTS:** The absolute load to failure values of each repair device in the shear scenario were only marginally different from the tensile load scenario. However, the stiffness of several tested devices was markedly reduced in the shear scenario. In both scenarios, large differences of the load to failure and the stiffness between the implant types up to 5-fold were found ($P < .05$). The failure mode of several all-inside flexible repair devices was different in the shear versus tensile load scenario, while the failure mode of the rigid systems was similar in both scenarios. **CONCLUSION:** All-inside meniscal repair devices exposed to shear load scenarios have comparable maximum loads to failures as tensile load scenarios. However, the stiffness of the majority of the flexible meniscal repair implants in a shear load scenario is markedly reduced. The applied scenario also affects the failure mode in several flexible meniscal repair devices. **CLINICAL RELEVANCE:** Meniscal repair devices with sufficient stiffness and stability against shear loads may be favored for meniscal repair, especially within the midportion of the meniscus where shear loads occur during healing.

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1 **Tensile and Shear Loading Stability of All-Inside**
2 **Meniscal Repairs**

3
4 **An In Vitro Biomechanical Evaluation**

5

6

7 **Abstract:**

8

9 **Background:**

10 Most biomechanical studies for evaluation of the structural properties of
11 meniscus repairs have been performed in tensile loading scenarios
12 perpendicular to the circumferential meniscal fibers. However, meniscal repair
13 constructs are also exposed to shear forces parallel to the circumferential
14 meniscal fibers during healing particularly in the mid-portion of the meniscus.

15

16 **Hypothesis:**

17 Material properties of meniscus repair devices cannot be extrapolated from
18 tensile load to shear force scenarios.

19

20 **Study Design:**

21 Controlled laboratory study.

22

23 **Methods:**

24 In 84 harvested and isolated bovine lateral menisci following removal of
25 adjacent soft tissue, a standardized vertical lesion was set followed by repair
26 using all-inside flexible (FasT-Fix, FasT-Fix AB, RapidLoc) and rigid meniscal
27 repair devices (Meniscus Screw, Meniscus Arrow). 2.0-Ethibond vertical and
28 horizontal sutures were used as controls. The repaired meniscal construct
29 was tested in a tensile (parallel to the axis of the tested repair device) and

30 shear force scenario (perpendicular to the axis of the tested repair device) at
31 5mm/min and 37°C environmental temperature. Maximum load-to-failure,
32 stiffness, and failure mode were recorded.

33

34 **Results:**

35 The absolute load-to-failure values of each repair device in the shear scenario
36 were only marginally different to the tensile load scenario. However, the
37 stiffness of the most tested devices were markedly reduced in the shear
38 scenario. In both scenarios, large differences of the load-to-failure and the
39 stiffness between the implant types up to 5-fold were found ($P < .05$). The
40 failure mode of several all-inside flexible repair devices was different in the
41 shear force vs. tensile load scenario, while the failure mode of the rigid
42 systems was similar in both scenarios.

43

44 **Conclusions:**

45 All-inside meniscal repair devices exposed to shear force scenarios have
46 comparable maximum load-to-failures to tensile load scenarios. However, the
47 stiffness of the majority of the flexible meniscal repair implants in a shear
48 force scenario is markedly reduced. The applied scenario also affects the
49 failure mode in several flexible meniscal repair devices.

50

51 **Clinical Relevance:**

52 Meniscal repair devices with sufficient stiffness and stability against shear
53 loading may be favored for meniscal repair especially within the mid-portion of
54 the meniscus where shear forces are occurring during healing.

55

56 **Keywords:**

57 meniscus; meniscus repair; all-inside meniscal repair device; tensile load;
58 shear load; biomechanics

59

60

61 **Introduction**

62

63 Meniscal repair represents the gold standard for treatment of vertical
64 meniscus tears within the vascularized zone, if healing can be biologically
65 expected.^{3, 4} However, surgical repair may be technically demanding and
66 time-consuming. Various rigid or flexible meniscal repair systems have
67 therefore been developed for the purpose. Of particular interest are all-inside
68 repair systems which have been primarily designed to facilitate the otherwise
69 technically difficult repair of the posterior horn.¹⁰

70 Overall, the mechanical stability of surgical soft tissue repair procedures
71 should ideally restore the mechanical properties of the native tissue. With
72 respect to the biomechanical loading patterns of the native menisci, which
73 include not only compression and distraction forces, but also shear forces
74 within the collagen fiber system of the meniscus as well as the adjacent
75 meniscocapsular area, the meniscal repair device must withstand these
76 various load impacts until healing has occurred. Distraction forces are not the
77 primary factor for the mechanical stability of meniscal repair within the healing
78 period. Other risk factors such as shear forces may be of greater significance
79 for failure of meniscal repairs.⁶

80 In most biomechanical studies, however, the repaired meniscal constructs
81 were mostly exposed and tested to distraction loading scenarios with tensile
82 load perpendicular to the circumferential fibers of the meniscus,^{1, 5, 7-9, 14, 16, 19}
83 while shear force scenarios are rarely performed.^{10, 20} Fisher and coworkers¹⁰

84 first studied ultimate shear tests of meniscal repair devices *in vitro*, and
85 Zantop and collaborators²⁰ performed cyclic loading of meniscal repairs in an
86 axial distraction and shear force scenario using horizontal and vertical
87 outside-in suture techniques. But to our knowledge, no data are available for
88 currently and commonly used all-inside meniscal repair devices in a shear
89 loading “worst-case” scenario.

90 In addition, environmental test temperature may have a considerable impact
91 on the material properties of bioabsorbable or partially bioabsorbable meniscal
92 repair implants, such as the FasT-Fix AB (absorbable), RapidLoc, Meniscus
93 Screw, and Meniscus Arrow. Biomechanical studies of bioabsorbable suture
94 anchors have demonstrated inferior biomechanical strength at 37°C (body
95 temperature) compared to 20°C (room temperature).¹²

96 The objective of the study was therefore to evaluate the biomechanical
97 properties of bioabsorbable, partially bioabsorbable, and non-bioabsorbable
98 all-inside meniscus repair systems *in vitro* using a standardized “worst-case”
99 tensile load vs. shear force scenario in a body temperature environment. We
100 hypothesized that (1) the mechanical performance of the meniscal repair
101 systems within tensile load scenarios cannot be extrapolated to shear force
102 scenarios and that (2) the failure mode is dependent on the applied test
103 scenario.

104

105

106 **Materials and Methods:**

107

108 **Specimen Preparation**

109 The intact lateral menisci of 84 freshly slaughtered bovine (age 5-10 months)
110 knee joints were harvested. The adjacent tissue except the adhering capsule
111 was removed. The anterior-posterior-diameter of the lateral menisci averaged
112 6 cm. Only intact and complete lateral menisci without any macroscopic
113 degenerative changes were selected for biomechanical testing. The specimen
114 were stored at -21°C prior final preparation, meniscal repair, and
115 biomechanical evaluation. One hour before testing, a standardized artificial
116 vertical lesion was created 4 mm apart from the peripheral meniscal rim within
117 the mid-portion of the meniscus (Figure 1A) representing a bucket-handle tear
118 within the red-red zone of the meniscus. Due to the unequal loading
119 directions in the tensile loading and the shear force scenario, the meniscal
120 part adjacent to the repair zone was prepared differently: In the tensile
121 loading scenario, the vertical lesion was completed over the entire meniscal
122 mid-portion (Figure 1B), while in the shear force scenario, the vertical lesion
123 was completed in a Z-shaped mode (Figure 1C). The artificial tear was
124 repaired using different all-inside meniscal repair devices according to the
125 instructions of the manufacturers. In detail, 3 flexible implant systems (FasT-
126 Fix [horizontal suture technique], FasT-Fix AB (absorbable) [horizontal suture
127 technique], RapidLoc) and 2 rigid implant systems (Meniscus Screw,
128 Meniscus Arrow) were tested. The main difference between the tested flexible
129 and the rigid implant devices is that the flexible devices include suture

130 material in addition to their backstop system, while the rigid devices are
131 absent of suture material. As two control groups representing an inside-out
132 technique, either a vertical or a horizontal 2.0 Ethibond (Ethicon, Norderstedt,
133 Germany) suture loop technique was performed. Each meniscus tear was
134 repaired utilizing one implant and each meniscus-implant-construct was
135 tested only once. Each implant type encompassed six single tests in each test
136 scenario representing overall 84 experiments. Thirty minutes prior and during
137 biomechanical testing, the repaired menisci were stored in a physiological
138 fluid solution (Ringer, B. Braun Medical Inc., Bethlehem, PA, USA) at 37°C
139 according to a physiological body temperature. Automatic stirring and
140 continuous measurement of the temperature was performed for maintaining
141 the equilibration of the fluid temperature.

142

143 **Biomechanical Tensile Testing**

144 Tensile Testing was accomplished using a uniaxial material testing machine
145 (universal testing instrument model 4204, Instron Corporation, Canton, MA,
146 USA) equipped with a 5000 N load cell (Instron Corporation). In both tensile
147 load and shear force scenarios, the mid-portion of the meniscus was mounted
148 to a custom-made metallic tissue clamp (Figure 2A) and the peripheral part of
149 the meniscus was fixed with a specifically designed mechanical interlocking
150 system. In detail, two stiff metallic batons were interposed within the artificial
151 meniscal tear adjacent to the repair area parallel to the circumferential
152 meniscal collagen fibers in the tensile load scenario (Figure 2A). In contrast,

153 one stiff metallic baton was interposed within the Z-shaped lesion
154 perpendicular to the circumferential meniscal collagen fibers in the shear
155 force scenario (Figure 2B). These fixation devices enabled a rigid interface
156 between the meniscal tissue and the clamp as well as the mounting system.
157 The custom-made tissue clamp was attached via a universal joint to the
158 crosshead of the material testing machine, and the mechanical interlocking
159 system was fixed to a stationary post within the physiological water bath
160 (Figure 2C).

161 In the tensile load and in the shear force scenario, the force of the tensile
162 testing was applied parallel and perpendicular to the meniscal repair
163 construct, respectively (Figure 1B and 1C). Both test setups ensured an
164 isolated testing for evaluation of the material properties of the meniscus-
165 implant-construct in tensile and shear loadings. Prior to testing, the repair
166 device-meniscus-construct was mechanically preconditioned with 5 N for
167 equilibration of the strain. The test speed of the mechanical loading was 5
168 mm/min according to Albrecht-Olsen et al.¹ and Borden et al.⁹ until structural
169 failure occurred. Structural failure was defined as the point beyond the
170 maximum load-to-failure represented by negative slope of the load/elongation
171 curve. Maximum load-to-failure and stiffness were determined as the maximal
172 load of the load/elongation curve and the slope of the linear portion of the
173 curve, respectively. In addition, the failure modes of the meniscus-implant-
174 construct were analyzed.

175

176 **Statistics**

177 For achievement of a Gaussian normal distribution, a square root
178 transformation of the parameter “stiffness” was necessary. SPSS 11.0
179 (SPSS, Chicago, Illinois, USA) was used for analysis of variance (ANOVA).
180 Post-hoc Bonferroni correction was applied based on multiple comparisons.
181 The level of significance was set at $P < .05$.

182

183

184 **Results:**

185

186 **Load-to-Failure**

187 Maximum load-to-failures of the tested all-inside meniscal repair devices and
188 the control groups are shown in Figure 3. Overall, the maximum load-to-
189 failures of each implant type did not differ significantly in the shear force
190 compared to the tensile load scenario. However, the RapidLoc, the Meniscus
191 Screw, and the Meniscus Arrow demonstrated significantly ($P < .05$) lower
192 maximum load-to-failures in both scenarios compared to Ethibond 2.0 vertical
193 or horizontal loops as well as to the FasT-Fix and FasT-Fix AB. In detail, the
194 Meniscus Screw and the Meniscus Arrow had up to 5 times lower maximum
195 load-to-failure values compared to the other tested all-inside meniscal repair
196 devices.

197

198 **Stiffness**

199 The stiffness of the tested all-inside meniscal repair devices are illustrated in
200 Figure 4. In all cases except in the RapidLoc and the Meniscus Screw, the
201 stiffness was lower in the shear force vs. the tensile load scenario. In the
202 Ethibond 2.0 vertical and the horizontal loop as well as in the FasT-Fix, the
203 lower stiffness in the shear force scenario reached the significance level ($P <$
204 $.05$).

205

206 **Failure Mode**

207 In all experiments, a slippage of the meniscal tissue within the interlocking
208 system was observed neither on the mounting nor on the clamping system
209 site. In 100% of the cases, the weakest link was the meniscal repair device or
210 the interface between the meniscal repair device and the meniscal tissue. The
211 failure modes of the tested all-inside meniscal repair devices are listed in
212 Table 1. Overall, the applied force scenario had a considerable influence on
213 the failure mode of the meniscus-implant-construct. In most of the flexible
214 meniscal repair devices (FasT-Fix and FasT-Fix AB), the typical failure mode
215 in the shear force scenario was breakage of the suture at the knot, while in
216 the axial force scenario the breakage of the suture occurred at the eyelet
217 (Figure 5). In the RapidLoc device, however, in more than 40% not the suture
218 itself, but the bioabsorbable backstop system was the weakest link of the
219 meniscus-implant-construct. In none of the cases of flexible meniscal repair
220 devices, a cutting of the suture through the meniscal tissue was observed. In
221 contrast, the failure mode of the rigid implants was predominantly located at

222 the interface between the implant and the meniscus tissue due to slippage of
223 the implant. This failure mode was independent of the applied force scenario.

224

225 **Discussion:**

226 Little information exists on the mechanical performance of meniscal repair
227 devices under shear load.^{10, 20} Shear load, however, is one of the
228 predominant forces acting on the meniscus with flexion and extension
229 movements of the knee.^{6, 10} Therefore, the objective of this study was to
230 evaluate the biomechanical properties of all-inside meniscal repair devices in
231 a “worst-case” tensile load vs. shear force scenario in a controlled laboratory
232 setup at a body temperature environment and under physiological fluid
233 conditions.

234 The most unexpected result was, that under shear load the stiffness of the
235 repair construct with either the suture or the FasT-Fix system was significantly
236 decreased, while in the repair with the RapidLoc, the Meniscus Screw and
237 Meniscus Arrow this significant effect was not seen. However, the decreased
238 stiffness of the aforementioned devices did not negatively affect the ultimate
239 strength of these meniscal repair constructs under shear load. Indeed, the
240 maximum load-to-failures of the tested meniscal repair devices was not
241 significantly altered between shear compared to the tensile load scenario.
242 Another interesting finding was, that the failure mode of the flexible, but not of
243 the rigid implants, did considerably differ between the shear force and the
244 tensile load scenario. It seems that the weakest link of the flexible all-inside

245 repair devices, especially in the FasT-Fix and the FasT-Fix AB device, does
246 change its location depending on the applied force scenario. In contrast,
247 slippage of the rigid implants was observed in all but one case independently
248 of the applied force. Overall, the first hypothesis that the mechanical
249 performance of the meniscal repair systems within tensile load scenarios
250 cannot be extrapolated to shear force scenarios was only confirmed for the
251 stiffness, but not for the maximum load-to-failure of some flexible all-inside
252 meniscal repair devices. In other words, most of the meniscal repair devices
253 demonstrate similar biomechanical properties in tensile load compared to
254 shear force scenarios, however, significant differences of the maximum load-
255 to failure and the stiffness can be found between the tested implant types.
256 The second hypothesis was confirmed for the flexible, but not for the rigid all-
257 inside meniscus repair devices that the failure mode is dependent on the
258 applied test scenario.

259 Many biomechanical studies have evaluated the meniscal repair devices *in*
260 *vitro* using a uniaxial axial distraction setup,^{1, 5, 7-9, 14, 16, 17} while meniscus
261 tears may occur most commonly secondary to a twisting force in combination
262 with an axial load, subjecting the meniscus to shear forces under
263 simultaneous compressive loading.¹⁰ However, biomechanical testing of
264 meniscal repair techniques in an *in vitro* shear force scenario was only rarely
265 performed.^{10, 20}

266 Fisher and coworkers¹⁰ were the first who evaluated meniscal repair devices
267 using a shear loading scenario. They found significant differences in peak

268 loads of the meniscus repair in an axial vs. shear force setup. While the
269 Meniscus Arrow performed better under axial load, the T-Fix Anchor
270 (precursor model of the FasT-Fix) demonstrated superior results in load-to-
271 failure under shear loading.¹⁰ In contrast, our results do not indicate any
272 significant differences of the ultimate load-to-failures in the shear load
273 scenario compared to the axial load scenario; however, considerable
274 differences up to 5-fold can be found between flexible and rigid meniscal
275 repair devices in both setups. The different results of our study compared to
276 Fisher et al.¹⁰ may be due to a different fixation technique of the meniscus,
277 variable material testing machine, test speed, and test temperature.

278 Zantop and coworkers²⁰ have investigated the structural properties of a
279 horizontal and vertical meniscal suture repair technique in an axial distraction
280 and shear force scenario under cyclic loading. Interestingly, they have found
281 that meniscal repair with a horizontal suture technique can withstand
282 elongation due to shear forces more effectively than a vertical suture
283 technique which may be important for limitation of meniscal tissue
284 displacement at the meniscal repair site during the healing process. However,
285 this significant difference of elongation at the repair site between horizontal
286 and vertical inside-out suture techniques did not influence the stiffness and
287 the maximum load of the corresponding repaired meniscus construct in the
288 shear compared to the axial distraction force scenario,²⁰ which is consistent
289 with our results. The unequal peak levels of the load-to-failure and stiffness in

290 both studies may be explained by the variable test protocol (cyclic vs. non-
291 cyclic), test speed, test temperature, and animal model.

292 It is yet unclear which quantity and quality of distraction, compression, and
293 shear forces are needed for structural damaging of the meniscus. In addition,
294 only limited data are available for the biomechanical prerequisites of sufficient
295 stabilization of the meniscal repair site during healing. In a controlled
296 laboratory study, Becker et al.⁶ demonstrated that distraction forces are not
297 the primary factor compromising the mechanical stability of meniscus repair
298 construct. They concluded that other forces, e.g. shear forces, may be
299 considered as a greater risk factor for jeopardizing the meniscal repair
300 integrity until healing has occurred.⁶

301 Limitations of our study are the isolated testing configuration using a uniaxial
302 and continuously acting tensile load or shear force setup, which represents
303 the loading conditions of the repaired meniscus *in vivo* only in parts, since the
304 meniscal repairs are also exposed to compression forces and cyclic loading.^{6,}

305 ^{15, 18, 20} Usually, critical axial distraction forces do not occur at the meniscal
306 repair site since compression forces counteract the distraction forces within
307 the healing period if correct rehabilitation is performed. However,
308 unpredictable loading of the knee within the rehabilitation period by undesired
309 squatting, pivoting, or twisting motions may cause deleterious distraction at
310 the repair site. Another limitation might be the utilization of bovine instead of
311 human menisci. However, structural, morphometrical, and biomechanical
312 properties of the bovine meniscus approximately resemble the properties of

313 the human meniscus.¹³ Therefore, we believe this limitation seems
314 advantageous compared to the alternative of cadaveric human menisci
315 obtained from elderly donors, which usually show random degenerative
316 alterations. In addition, several biomechanical studies of meniscal repair have
317 been performed on bovine meniscus.^{1, 2, 8, 11, 14}

318 The impact of the test temperature on the mechanical properties of
319 bioabsorbable or partially bioabsorbable all-inside meniscal repair devices
320 has yet to be determined. Certainly, body temperature and physiological fluid
321 environment represents the *in vivo* conditions more closely than room
322 temperature and ambient air, respectively. Arnoczky and Lavagnino²
323 demonstrated a significant impact of environmental fluid temperature on the
324 hydrolysis time of several bioabsorbable meniscal repair devices over a 24-
325 week period. In our study, however, relevant hydrolysis of the bioabsorbable
326 materials within the physiologic water bath at body temperature will not occur
327 within our short-term test period. Since Meyer et al.¹² observed inferior
328 biomechanical properties of bioabsorbable suture anchors at body compared
329 to room temperature, bioabsorbable meniscal repair devices may be also
330 susceptible to higher test temperature which may mislead to a systematic
331 overestimation of their mechanical properties at room temperature. However,
332 body temperature and fluid environment are so far neglected test parameters
333 in most biomechanical meniscus repair studies.^{1, 5, 6, 8-11, 14, 16, 17, 19, 20}
334 Therefore, we have privileged the higher test temperature (body temperature)

335 in a physiological fluid environment even accepting limited comparability to
336 other biomechanical studies performed at room temperature.

337 In conclusion, the present study showed that all-inside meniscal repair
338 devices exposed to shear force scenarios have comparable maximum load-
339 to-failures to tensile load scenarios. However, the stiffness of the majority of
340 the flexible implants in a shear force scenario is markedly reduced. Especially
341 repair of the central portion of the meniscus where shear forces are occurring
342 while passive and active knee motions, meniscal repair devices with sufficient
343 stiffness and stability against shear loading may be favored in this area. To
344 our knowledge, this is the first study analyzing commonly used all-inside
345 meniscal repair devices in a shear force vs. tensile load scenario at a
346 physiological fluid environment and body temperature. Further studies may
347 focus on combined tensile, shear, and compression loads which simulate the
348 *in vivo* conditions more closely.

349

350

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352

353

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- 421
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- 423

424 **Tables:**

425

426 Table 1 Failure Modes of All-Inside Meniscal Repair Devices in Tensile
 427 Load vs. Shear Force Scenario Compared to Vertical and Horizontal Ethibond
 428 2.0 Suture Loops.

429

Implant System		Failure Mode	
Brand Name	Company	Tensile Load Scenario	Shear Force Scenario
Ethibond 2.0 (vertical)	Ethicon	6x knot breakage	6x knot breakage
Ethibond 2.0 (horizontal)	Ethicon	6x knot breakage	6x knot breakage
FasT-Fix (horizontal)	Smith & Nephew	2x knot breakage 4x eyelet suture breakage	5x knot breakage 1x eyelet suture breakage
FasT-Fix AB (horizontal)	Smith & Nephew	1x knot breakage 5x eyelet suture breakage	4x knot breakage 2x eyelet suture breakage
RapidLoc	DePuy Mitek	3x suture breakage 3x eyelet breakage	4x suture breakage 2x eyelet breakage
Meniscus Arrow	Linvatec	5x migration of Arrow 1x Arrow head breakage	6x migration of Arrow
Meniscus Screw	Arthrotek	6x migration of Screw	6x migration of Screw

430

431

432

433 **Figure Legends:**

434

435 **Figure 1** Preparation of the bovine lateral meniscus. A, The anterior and
436 the posterior horn of the lateral meniscus was removed for testing the mid-
437 portion of the meniscus. Subsequently, a standardized vertical lesion within
438 the mid-portion of the meniscus 4 mm apart from the peripheral rim was set.
439 B, Adjacent to the meniscal repair zone, the lesion was completed in the
440 tensile load scenario; C, a modification of the cutting technique of the
441 adjacent meniscal tissue was necessary for sufficient fixation in the shear
442 force scenario. Fixation points and direction of loading (arrow) are illustrated;
443 red rectangle represents meniscal repair area (figure without meniscal repair
444 device).

445

446 **Figure 2** Biomechanical setup for isolated testing of tensile and shear
447 loading on the meniscus-repair device-construct. A, Setup of the interlocking
448 system setup for tensile load testing (anterior metallic baton partially retrieved
449 for visualization of the peripheral meniscal rim) including the metallic clamp;
450 B, setup of the interlocking system for shear force loading (direction of loading
451 is illustrated by arrows; red rectangle represents meniscal repair area); C,
452 material testing machine including physiologic water bath and temperature
453 control unit.

454

455 **Figure 3** Average load-to-failure ($\pm$ SD) of the tested meniscal repair
456 systems in tensile vs. shear force scenario.

457 * $P < .05$ compared to Ethibond 2.0 vertical, Ethibond 2.0 horizontal, FasT-Fix
458 (horizontal), and FasT-Fix AB (horizontal).

459

460 **Figure 4** Average stiffness ($\pm$ SD) of the tested meniscal repair systems in
461 tensile vs. shear force scenario.

462 * $P < .05$ tensile vs. shear force stiffness in Ethibond 2.0 vertical, Ethibond 2.0
463 horizontal, and FasT-Fix (horizontal).

464

465 **Figure 5** A, knot breakage of the FasT-fix predominantly observed in the
466 shear force scenario; B, suture breakage at the eyelet of the FasT-Fix
467 predominantly found in the tensile load scenario.

468

469

Figure 1

Figure 1

Figure 1

Figure 2

Figure 2

Figure 2

Figure 3

Figure 4

Figure 5

Figure 5