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1. PROXIMAL TIBIAL BONY AND MENISCAL SLOPES ARE HIGHER IN 2. ACL INJURED SUBJECTS THAN CONTROLS. A COMPARATIVE MRI 3. STUDY.

4. ABSTRACT

5. PURPOSE: Increased tibial slope is reported as a risk factor of non-contact anterior

6. cruciate ligament (ACL) injury, but the effect of the soft tissues on slope remains

7. unclear. The primary aims of this study were to compare the tibial bony and soft tissue

8. slopes between patients with and without ACL injury, and to investigate the

9. relationship between the meniscal slopes (MS) and the tibial bony slope. Our

10. hypothesis was that the menisci would correct the inclination of the bony tibial slope

11. towards the horizontal.

12. METHODS: Using Magnetic resonance imaging (MRI), the lateral & medial tibial slopes

13. (LTS, MTS) and lateral & medial meniscal slopes (LMS, MMS) were compared in 100

14. patients with isolated ACL injury and a control group of 100 patients with patello-

15. femoral pain and an intact ACL.

16. RESULTS: Repeated measures analysis of variance showed good inter- & intra-observer

17. reliability for both bony and soft tissue slopes (ICC **(0.88-0.93)** and **(0.78- 0.91)** for intra-

18. & inter-observer reliability, respectively). The LTS & MTS were significantly greater in

19. the ACL injury group **(10.4±3.1 & 9.4±3.3)** than in the control group **(7.3±3.4 &**

20. **7.0±3.7**). Similarly, the LMS & MMS were significantly greater in the ACL injury group
21. **(4.7±4.7 & 6.0±3.4)** than the control group **(0.9±4.8 & 3.7±3.6)**. In both
22. groups, the lateral bony tibial slope was greater than the medial bony tibial slope, but
23. the medial soft tissue slope was greater than the lateral soft tissue slope.
24. **CONCLUSION:** Increased tibial slopes, both bony and meniscal, are risk factors for ACL
25. injury. As the meniscus tends to correct the observed slope towards the horizontal, loss
26. of the posterior meniscus may potentiate this effect by increasing the functional slope.
27. **LEVEL OF EVIDENCE:** Level III.
28. **KEYWORDS:** Knee, Tibial slope, Anterior Cruciate Ligament Injury, Meniscus, MRI.

29. **INTRODUCTION:**

30. ACL injury occurs predominantly via non-contact mechanisms. Due to the high
31. incidence of long-term sequelae of ACL injury, including pain, instability, and the early
32. development of osteoarthritis, identification of risk factors for ACL injury is an important
33. step in the development of injury prevention **(33)**.
34. Recently in the literature, there has been a great focus on anatomic risk factors.
35. Posterior Tibial slope (PTS) is commonly defined as the angle between a line fit to the
36. posterior-inferior surface of the tibial plateau and a tibial anatomic reference line **(14,**
37. **15, 17, 18, 23, 30, 32)**.
38. Biomechanically, a higher tibial slope in the presence of a compressive load will

39. generate a higher anterior shear component of the tibio-femoral reaction force,
40. resulting in increased anterior motion of the tibia relative to the femur. Because the ACL
41. is the primary restraint against this type of motion in the knee, it logically follows that
42. an increase in the posterior tibial slope will generate an increased load in the ACL. This
43. hypothesis was first noted by Butler in 1980 **(4)**.
44. Reliable clinical measurements of posterior tibial slope are important for understanding
45. ACL injury mechanisms. It is widely mentioned in the literature that ACL-injured
46. individuals have a greater posterior tibial slope than healthy controls **(20)**.
47. It remains unclear whether the risk of non-contact ACL injury is increased in
48. those with increased slope in one or both compartments, and individual analysis of the
49. compartments separately could be essential to understand the functional consequences
50. of tibial slope **(21)**.
51. The medial and lateral PTS are not necessarily identical in one given knee and
52. differences of as much as 27° have been reported in cadaveric studies **(16)**.
53. Various models for PTS measurement on conventional lateral radiographs have been
54. described, however it is still imprecise. Due to superimposition of the hemi-plateaus,
55. the lateral tibial plateau is difficult to identify, and separate assessment of the plateaus
56. is not reliably possible on lateral radiographs **(16)**.
57. Previous studies have validated different modalities for measuring posterior tibial slope
58. **(20)**. No significant difference exists between radiographs, computed tomography, and
59. magnetic resonance imaging (MRI); recent work has focused on MRI **(20, 29)**. Although
60. lateral radiographs are better to assess the medial PTS, they are inadequate for reliable

61. and separate PTS and meniscal slope (MS) assessment (16). Therefore, it is
62. recommended to use conventional MRI scans of the knee, as they allow simple
63. assessment of each plateau separately, and provide the possibility to assess the MS
64. reliably (15), while methods using three-dimensional computed reconstructions are
65. time-consuming and complex (12).

66. The soft tissues (e.g. cartilage and meniscus) play a role in antero-posterior stability of
67. the knee joint and may influence the functional tibial slope. The posterior
68. horn of the menisci is thicker than the anterior horn, and this could decrease the
69. postero-inferior slope (19).

70. This study aims to evaluate the correlation between the tibial slope and non-
71. contact ACL– injury using MRI, as well as to determine the effects of the menisci on
72. tibial slope.

73. It was hypothesized that the meniscus would reduce the differences in slope
74. between the medial and lateral compartments of the same knee. In addition, it
75. was hypothesized that the presence of the meniscus would correct the
76. inclination of the bony tibial slope towards the horizontal.

77. MATERIALS AND METHODS:

78. All patients referred to the Croix-Rousse Hospital between 2012 and
79. 2015 for consideration of knee interventions were eligible for
80. inclusion in the study. The inclusion criteria were an MRI scan, with adequate quality
81. images available on the Picture Archiving and Communication (PACS) system and

82. a report detailing the status of the ACL. Exclusion criteria were osteoarthritis, patients
83. with open physes or under the age of 18 years, MRI evidence of intra-articular
84. pathology besides ACL tear, prior surgery to the involved knee, and those where the
85. scanned length of the tibia was insufficient for calculation of the tibial axis.
86. Two groups of patients were thus established. The study group consisted of 100
87. patients (67 males & 33 females) with MRI confirmed isolated partial or complete
88. rupture of the ACL. Patient age in this study group ranged from 18- 63 (Mean $\pm$ SD,
89. 33.7 $\pm$ 10.8). The control group consisted of 100 patients whose major complaint was
90. patello-femoral pain (52 males & 48 females), and whose MRIs revealed an intact ACL.
91. Patient age in this control group ranged from 18 -86 (Mean $\pm$ SD, 43.6 $\pm$ 15.9).
92. MRIs were obtained from a single 1.5-T MRI scanner (manufacturer-supplied
93. quadrature head coil, Philips Medical Systems). Proton density sagittal slices were used
94. to measure the angles. All measurements of the bony tibial slope and meniscal slope
95. angles were carried out using the annotation tools on the PACS provided by the
96. hospital, which allows tracing of the anatomical landmarks, connecting regions of
97. interest, and measurements of different angles. We chose three sagittal images from
98. the corresponding axial cuts at the joint line for three different cut regions: the mid-
99. sagittal cut, which use for calculating the proximal tibial anatomic axis (PTAA) (**Figs.**
100. **1&2**), the mid-lateral tibial plateau cut (LTP) (**Figs. 3, 4&5**), and the mid-medial tibial
101. plateau cut (MTP) (**Figs. 6, 7&8**).
102. Two independent reviewers, blinded to subjects' details, calculated the angles on each
103. MRI using a modified Hashemi method described previously by Lustig et al (**21**).

104. The first observer performed two sets of measurements for each subject, two weeks
105. apart. The second observer, blinded to the results of the first, repeated the
106. measurements in a random specimen order.

107. To establish the tibial slope, we used PTAA which demonstrates the best correlation
108. with the tibial shaft anatomic axis (TSAA) **(6)**. The PTAA is described on the mid-sagittal
109. cut by a line joining the midpoint between the anterior and posterior tibial cortices at
110. the level of the tibial tuberosity and at another level 5 cm more distal. The angle
111. between the tibial axis and the horizontal was then calculated (PTTA-H
112. Angle). This angle was used to transfer the PTAA among different images.

113. The MTP and LTP cuts were used to measure the medial and lateral tibial slopes (**MTS**,
114. **LTS**) respectively. The PTAA was superimposed onto these cuts by means of the PTTA-H
115. angle. The tibial slope in each compartment was measured as the angle between a line
116. connecting the highest points of the anterior & the posterior parts of the tibial plateau,
117. and a line perpendicular to the PTTA. A posterior inclination to the line perpendicular
118. to the PTAA was assigned a positive value, while an anterior inclination was assigned a
119. negative value.

120. All measurements were positioned as an overlay and remained in a fixed position on
121. the complete image series. The lateral meniscal slope (**LMS**) and medial meniscal slope
122. (**MMS**) were defined in the same manner as the PTS. A line joining the superior edge of
123. the meniscosynovial border of the anterior and posterior horns of the meniscus in the
124. sagittal plane was chosen instead of the tibial plateau cortex.

125. **STATISTICAL ANALYSIS:**

126. The PTS and MS angles were reported as mean angles with standard deviations.
127. Data were statistically analyzed using SPSS for Windows statistical package
128. (version 11.5; SPSS, Chicago, IL, USA). The assumption of normality was assessed with
129. Kolmogorov–Smirnov tests. Intra-observer & inter-observer reliability was tested by
130. means of Intra class Correlation Coefficient (ICC) to establish whether the mean slope
131. was altered between repeated measurements of the two observers.
132. Independent two sample t-test was used to compare the four variants between the two
133. groups. We calculated a sample size of 95 subjects was required, to achieve 90% power
134. to reject the null hypothesis ($\alpha = 0.0001$).

135. **RESULTS:**

136. The test of normality revealed that all measured parameters for both groups were
137. normally distributed ($p < 0.0001$). The data were initially analyzed for each reviewer
138. and then the parameters were compared between the two groups.

139. **Intra-observer & inter-observer reliability:**

140. The inter-observer ICC for all variants of the ACL group ranged
141. from 0.89 to 0.91 and for the control group from 0.87 to 0.90. Similarly, the
142. intra-observer ICC was high (0.88-0.93) which reveal strong agreement between
143. observers for all measurements.

144. The means, standard deviations (**SD**) and ranges for the repeated measurements **LTS**,
145. **MTS**, **LMS**, and **MMS** for the examined and control groups are shown in the **table (1)**.

146. For the ACL injury group, the **LTS** ranged from 1.9° to 15.8° and the **MTS** ranged

147. from 1.4° to 16° while the **LMS** ranged from -5.6° to 13.8° and the **MMS** ranged from
148. -2.2° to 14.5° . Similarly, for the control group the **LTS** ranged from 0° to 15.4° , and
149. the **MTS** ranged from -0.6° to 15.0° while the **LMS** ranged from -12.5° to 12.6° and
150. the **MMS** ranged from -4.2° to 11.5° . In the analysis of the ACL injury group the **LTS**
151. was larger than the **MTS** but the **LMS** was smaller than **MMS**. In the control group, the
152. **LTS** was also larger than the **MTS** and the **LMS** was smaller than **MMS** (fig.9).
153. **Comparison of the variants of the two groups:**
154. By direct comparison of the two groups, using independent a two sample student's t-
155. test, the LTS & MTS were significantly greater in the ACL injury group than the control
156. group (p was 6.76 for LTS & 4.85 for MTS). Similarly, the LMS & MMS were significantly
157. greater in the ACL injury group than the controls (p was 5.67 for LMS & 4.61 for
158. MMS).

159. **DISCUSSION:**

160. The most important finding of this study is that the lateral and medial bony and soft
161. tissue slopes were all significantly higher in the ACL injured group compared to the
162. control group. In both groups, the lateral bony tibial slope was greater than the medial
163. bony tibial slope, but the medial soft tissue slope was greater than the lateral soft
164. tissue slope. These findings are generally consistent with the published literature
165. (Table 2).

166. Regarding the bony slope, Brandon et al compared the radiographic posterior
167. inferior tibial slope, as measured on plain radiographs, between ACL injured
168. subjects and controls **(2)**. They found an increased slope in the ACL injured group,
169. and that within the ACL injured group, increased slope correlated with increased
170. severity of the pivot shift. Stijak et al, using radiographs to establish the PTAA and then
171. MRI to measure the bony slope in each compartment, found an increased lateral bony
172. slope in ACL injured subjects **(24)**. Hashemi et al, in an MRI study, found increased
173. lateral tibial plateau slope and decreased medial plateau concavity in the ACL injured
174. group in both sexes, as well as an increased medial slope in ACL injured males **(13)**.
175. Similar results have also been reported in the pediatric population **(6, 22)**. Not all
176. studies have supported these findings. Blanke et al, in a study of recreational skiers,
177. found no difference in the lateral or medial slope, or medial plateau concavity, between
178. ACL injured and non-injured subjects **(1)**. Hudek et al examined not only the bony tibial
179. slopes, but also the influence of the menisci or the soft tissue slope **(15)**. In contrast to
180. the aforementioned studies, they found no difference between ACL injured and
181. healthy controls with regards to the bony lateral and medial slopes. However, they
182. found increased lateral meniscal slope in the ACL injured group. Lustig et al examined
183. the effect of the meniscus on the observed slope in non-ACL injured subjects **(21)**. In
184. line with the findings of our study; they found the meniscal slope to be more horizontal
185. than the bony slope in both compartments, with the lateral meniscal slope closer to
186. horizontal than the medial meniscal slope. Bonnin and Dejour investigated the impact
187. of the tibial slope on knee biomechanics, they found a 6mm increase in anterior

188. translation for each 10° increase in slope in healthy and ACL deficient knees **(8)**. In a
189. cadaveric study, Giffin noted an increase in anterior tibial resting position with
190. increased tibial slope that was accentuated under an axial load **(10)**.
191. The effects of patient demographics, such as gender and age, on the tibial slope have
192. not been fully elucidated. Females are at greater risk of non-contact ACL injury and a
193. steeper tibial slope has been observed in females **(21)**. Multiple studies have shown
194. that women have a greater propensity for ACL injury compared to their male
195. counterparts **(11, 13, 15, 24, 33)**. It has been suggested that a possible risk factor for
196. this observation is that women have a narrower notch than men and even smaller ACLs.
197. Differences in slope between the medial and lateral compartments may also have
198. biomechanical consequences. Under a compressive load, the lateral femoral condyle
199. has been postulated to slide posteriorly due to increased LTS, pivoting around the
200. medial femoral condyle. The resultant external femoral rotation has been shown to
201. place excess strain on the ACL **(9, 23)**.
202. Increased posterior slope is a risk factor not only for an ACL tear, but also for failure of
203. ACL reconstruction. Webb et al found an increased risk of failure or contralateral injury
204. associated with increased tibial slope, which was most apparent with the posterior
205. slope in excess of 12° **(31)**. Similarly, Christensen et al found increased lateral slope to
206. be associated with a risk of early failure, regardless of graft type **(5)**. Slope levelling
207. osteotomy has been proposed to correct this risk factor in repeat revision surgery **(9,**
208. **28)**.
209. The importance of the meniscal contribution to slope and knee biomechanics remains

210. unclear. While Lustig demonstrated more horizontal meniscal slopes when compared
211. to the bony slopes, this MRI based study could not evaluate the effect of joint loading
212. and meniscal mobility **(21)**. Song has defined the abnormal lateral plateau slope as a
213. risk factor for a high grade pivot shift **(27)**. Loss of the posterior lateral meniscal root
214. also increases lateral compartment anterior translation during a pivot shift maneuver
215. **(25)**. Under load, loss of the meniscal root could convert the effective functional slope
216. from the meniscal slope to the bony slope, which may explain these findings. Song, in a
217. separate study, also found increased medial meniscal slope to be a risk factor for ramp
218. lesions, particularly when time to surgery was greater than six months **(26)**.

219. An understanding of the anatomical risk factors for ACL injury and treatment failure is
220. important. While some factors, such as the width of the intercondylar notch, are not
221. readily modifiable, their identification may help to target proven prevention strategies
222. towards high risk individuals, in the same manner in which they are targeted towards
223. high risk sports. As a risk factor, increased tibial slope is potentially modifiable by
224. osteotomy. Such intervention should be considered in cases of excessive slope,
225. particularly after the loss of the menisci; however, the appropriate threshold for
226. intervention remains unclear.

227. One of the greatest strengths of using MRI for this application is the ability to visualize
228. the surface geometry of the articular cartilage, which represents the functional point of
229. the tibiofemoral articulation. Our study presents a reliable method for
230. measurement of the tibial and meniscal slopes in both knee compartments, which
231. could be developed as a predictive tool for ACL risk. The aims of future research

232. relating PTS to ACL injury risk should be to establish not only the extent of the role of
233. tibial slope in injury, but also to which that risk can be minimized by preventive
234. measures such as neuromuscular training **(33)**.

235. This study is subject to a number of limitations. Firstly, all MRI scans were performed in
236. a recumbent position. Weight bearing may affect the meniscal height both anteriorly
237. and posteriorly and thus alter the measured meniscal slope. Furthermore, the control
238. group consisted of patients with patello-femoral pain, but no intra-articular pathology
239. as seen on MRI scans. While a similar group has been used in multiple previous studies
240. **(2, 15, 21, 24)**, these patients may in fact have tibial slope characteristics that differ
241. from a true asymptomatic population.

242. **CONCLUSION**

243. This study confirmed that the tibial bony & soft tissue slopes can be measured reliably
244. using an MRI-based method. Increased tibial slopes, both bony and meniscal, are risk
245. factors for ACL injury. As the meniscus tends to correct the observed slope towards the
246. horizontal, loss of the posterior meniscus may potentiate this effect by increasing the
247. functional slope.

248. **Competing interests:**

249. The authors declare that they have no competing interests.