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Hamstring-Dominant Strategy of the Bone–Patellar Tendon–Bone Graft Anterior Cruciate Ligament–Reconstructed Leg Versus Quadriceps-Dominant Strategy of the Contralateral Intact Leg During High-Intensity Exercise in Male Athletes

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1 **Hamstring-dominant strategy of the bone-patellar tendon-bone graft ACL**
2 **reconstructed leg vs. quadriceps-dominant strategy of the contra-lateral intact leg**
3 **during high intensity exercise in male athletes**

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26 **ABSTRACT**

27 **Purpose:** The purpose of the present study was to investigate the effect of the ACL
28 reconstruction on the quadriceps-dominant strategy as a parameter associated to the
29 neuromuscular control of the knee joint.

30 **Methods:** Fourteen ACL reconstructed competitive soccer players with bone-patella tendon-
31 bone autograft and fourteen healthy competitive soccer players performed two 10-min
32 treadmill runs, one at a moderate and one at a high intensity. Electromyographic recordings
33 were acquired using a telemetric system at the 3rd, 5th, 7th, and 10th minute of the runs from the
34 vastus lateralis and the biceps femoris bilaterally. The dependent variable examined was the
35 peak EMG amplitude during the stance phase. ANOVAs were used to examine significant
36 main effects and interactions.

37 **Results:** Vastus lateralis electromyographic activity during high intensity running increased
38 for both the control and intact leg ($F=4.48$, $p<0.01$) while it remained unchanged for the
39 reconstructed leg ($p>0.05$). Biceps femoris electromyographic activity during high intensity
40 running increased for the reconstructed leg only compared to both the control ($F=3.03$,
41 $p<0.05$) and intact leg ($F=3.36$, $p<0.03$).

42 **Conclusions:** There is no presence of a quadriceps-dominant strategy in ACL reconstructed
43 athletes during moderate intensity exercise. During high intensity exercise, the intact contra-
44 lateral leg develops a quadriceps-dominant strategy, whereas the reconstructed leg does not.
45 The reconstructed leg increases instead biceps femoris activity developing a “hamstring-
46 dominant” strategy and this “asymmetry” may theoretically be in favor of the reconstructed
47 knee.

48 **Level of Evidence:** III, retrospective comparative study of two groups

49

50

51 **INTRODUCTION**

52

53 After anterior cruciate ligament (ACL) reconstruction several alterations at the neuromuscular
54 control of the knee joint may develop including selective muscle fiber atrophy in the involved
55 quadriceps [1, 2], altered motor unit activation following surgery and subsequent retraining
56 [3] and loss of joint afferent information which may lead to suboptimal muscle fiber
57 activation [4]. These neuromuscular response perturbations of ACL-reconstructed knees may
58 affect the amount of stress that is applied on the ACL graft postoperatively due to selective
59 muscle activation, and thus may have important implications for the graft integrity. Moreover,
60 since relevant neuromuscular control strategies have been previously considered as potential
61 risk factors for native ACL injury [5, 6, 7] they most likely have dual interest in the case of an
62 ACL-reconstructed individual, namely their reconstructed and contralateral intact knee.

63

64 Even if pure muscular response is measured, the combined recordings from both anterior and
65 posterior thigh muscles activity may provide important information for the amount of stress
66 that is applied to the ACL (either native ACL or a graft substitute). For instance, the
67 quadriceps-to-hamstring ratio has been considered a parameter associated to neuromuscular
68 control that can affect the ACL integrity [7]. Since exercise intensity has been related to the
69 muscle activity [8, 9, 10] it would be reasonable to observe such neuromuscular response
70 parameters with reference to the exercise intensity. During moderate intensity activities such
71 as walking and jogging, ACL reconstruction re-establishes the extensor electromyographic
72 (EMG) activity of the operated leg towards normative values [11, 12, 13, 14]. On the
73 contrary, no relevant information exists regarding high intensity exercise of ACL-
74 reconstructed individuals. High intensity exercise represents a particular condition where
75 metabolic fatigue is accumulated and special neuromuscular demands evolve. The quadriceps-

76 dominant strategy that has been described for healthy subjects while performing high intensity
77 exercise consists of an increase in agonist (extensor) EMG activity without a concomitant
78 increase in antagonist (flexor) EMG activity [8, 15, 16]. This response is considered to
79 represent an optimization strategy to compensate for the deleterious effects of fatigue on joint
80 neuromuscular control [8, 15, 16].

81

82 However, the literature lacks of information about the neuromuscular response of the ACL-
83 reconstructed leg during high intensity exercise. In addition, it is unknown what the
84 neuromuscular response behavior of the intact contra-lateral knee of an individual with
85 unilateral ACL reconstruction is during high intensity activities.

86

87 The purpose of the present study was to investigate the effect of the ACL reconstruction on
88 the quadriceps-dominant strategy as a parameter associated to the neuromuscular control of
89 the knee joint during moderate and high intensity exercise. We hypothesized that (a) during
90 moderate intensity exercise there will be no evidence of quadriceps-dominant strategy for of
91 any the control, intact and reconstructed leg, (b) during high intensity exercise the quadriceps-
92 dominant strategy will be evident for the control and intact contra-lateral but not the
93 reconstructed leg.

94

95 **METHODS**

96 Two groups of athletes participated in the study. The first group consisted of a consecutive
97 series of fourteen ACL-reconstructed competitive male soccer players [mean (SD) age, body
98 mass and height, 24.8 (5.3) years, 77.3 (7.5) kg and 177 (5.3) cm with ACL-reconstructed
99 knees and the second group consisted of fourteen healthy competitive male soccer players
100 who had never suffered any kind of orthopaedic or neurological condition [mean (SD) age,

101 body mass and height, 21.7 (4.4) years, 72.2 (8.3) kg and 180 (9.0) cm]. The operated athletes
102 had undergone ACL reconstruction with bone-patella tendon-bone (BPTB) autograft, on
103 average 18.5 (SD 4.3) months before testing. ACL reconstruction was performed sub-acutely
104 within 6 months after the injury from the same surgeon (range 1 to 4 months). All subjects
105 had a unilateral ACL tear confirmed by MRI and arthroscopy.

106

107 All subjects underwent the same rehabilitation protocol, starting from the first post operative
108 day with the use of passive exercises. Return to sports was permitted 6 months after
109 reconstruction provided that the athletes had regained stability and full functional strength,
110 according to the following criteria [17]: (1) Full range of motion, (2) KT-1000 side-to side
111 difference <3mm, (3) quadriceps strength >85% compared to the contralateral side, (4)
112 hamstrings strength 100% compared to the contralateral side, (5) hamstrings-to-quadriceps
113 strength ratio >70% and (6) functional testing >85% compared to the contralateral side. Their
114 strength was determined with the BIODEX System-3 isokinetic dynamometer (Biodex Corp.,
115 Shirley, NY, USA), revealing acceptable symmetry in quadriceps and hamstrings strength, as
116 well as acceptable hamstring-to-quadriceps-ratio. All subjects agreed with the testing protocol
117 and gave their consent to participate in accordance with the Institutional Review Board
118 policies of our Medical School.

119

120 Prior to any data collection, a clinical evaluation was performed on all subjects by the same
121 clinician. During this evaluation, the Tegner and Lysholm scores were obtained, while
122 anterior tibial translation was evaluated using the KT-1000 arthrometer (MEDmetric Corp.,
123 San Diego, California) [18]. These measurements were performed using 134N posterior-
124 anterior external force at the tibia, as well as maximum posterior-anterior external force until

125 heel clearance. Repeated anterior tractions were performed until a constant reading on the dial
126 was registered.

127

128 The athletes reported to the laboratory on three different occasions, separated by 48 hours,
129 within a two weeks period. For their first visit to the laboratory, athletes performed an
130 incremental treadmill (Technogym Runrace 1200, Italy) running test to volitional exhaustion
131 with 3 minute-stages, to determine maximal aerobic power (VO_2max) and lactate threshold
132 (LT) [19]. A computerized system was used for all metabolic measurements (CPX Ultima,
133 Medical Graphics, St Maul, MN, USA). At the end of each stage, capillary blood samples
134 were collected and analyzed for lactate (Accutrend, Roche Diagnostics, Germany). Prior to
135 each test, all analyzers were calibrated according to the manufacturer instructions. Attainment
136 of VO_2max was verified according to criteria established by the American College of Sports
137 Medicine [18]. Lactate threshold was determined according to Cheng et al [20]. The high
138 intensity running was set at ~85-88 of VO_2max (HI) and the moderate intensity running was
139 set at ~80% of the lactate threshold (MOD) [21].

140

141 In each of the two subsequent visits to the laboratory, athletes were required to perform a 10-
142 minute run at the pre-selected intensities. We only tested one intensity at each visit and the
143 test order was randomly assigned for every athlete. During running, EMG data were collected
144 for 15 seconds at the 3rd, 5th, 7th and 10th minute. Gas exchange data were recorded
145 simultaneously breath-by-breath, heart rate was measured throughout the test and blood
146 lactate was measured prior to running and immediately after termination of exercise.
147 EMG traces were obtained from the vastus lateralis (VL) and biceps femoris (BF) muscles
148 bilaterally using bipolar, circular, pre-amplified, pre-geld Ag/AgCl electrodes with 10 mm
149 diameter and fixed inter-electrode spacing of 20 mm (Noraxon Inc, Scottsdale, AZ, USA).

150 EMG data were recorded with a wireless 8-channel EMG system (Telemetry 2400T, Noraxon
151 Inc, Scottsdale, AZ, USA) and displayed real-time on a personal computer using dedicated
152 software (MyoResearchXP, Noraxon Inc, Scottsdale, AZ, USA). The surface of the skin was
153 prepared by shaving hair, rubbing it with abrasive paper and cleaning it with alcohol. The
154 electrodes were fixed longitudinally over the muscle belly. For the VL the electrodes were
155 placed at the antero-lateral muscle bulge at 2/3 of the proximo-distal thigh length, while for
156 the BF the electrodes were placed at the dorso-lateral side of the thigh at 1/2 of the proximo-
157 distal thigh length [22, 23]. The visually largest area of muscle belly was selected using a
158 contraction against manual resistance. The ground electrode was placed on lateral femoral
159 condyle of the right leg. Electrodes and cables were secured with surgical tape, in order to
160 avoid any interference with the running pattern of the subjects.

161
162 Footswitches (Noraxon Inc, Scottsdale, AZ, USA) placed under the heel and big toes of both
163 legs were used to denote heel-strike and toe-off. Prior to the running, subjects performed a
164 “zero offset” function to establish a zero baseline for each of the EMG channels. EMG was
165 acquired at a sampling rate of 1500 Hz. The raw EMG was measured in a band of 10 to 500
166 Hz, was full-wave rectified, was high pass filtered (cut-off frequency at 20 Hz) with an 8th
167 order Butterworth filter to remove movement artifacts and was smoothed with a 100 ms RMS
168 algorithm. Values from 20 strides were averaged to calculate the mean peak amplitude during
169 stance for each of the four time intervals (FIGURE 1). The stance period was selected for
170 analysis because the ACL is stressed maximally during this portion of the gait cycle [24].

171 172 **Statistical analysis**

173 Based on our hypotheses, the dependent variable examined in the present study was the peak
174 EMG amplitude during the stance phase. A 2-way fully repeated ANOVA within the control

175 group, with time (four levels) and leg (two levels) as within-subjects factors, revealed no
176 time*leg interactions for the EMG amplitude for either the moderate or high intensity running
177 (data not shown). Thus, the left leg was selected as the control leg.

178 We compared the control with the intact contra-lateral and with the reconstructed leg using a
179 3-way mixed ANOVA with muscle (two levels) and time (four levels) as within-subjects and
180 groups (two levels) as between-subjects factors. Finally we compared the intact and
181 reconstructed leg using a 3-way fully repeated ANOVA with muscle (two levels), time (four
182 levels) and leg (two levels) as within-subjects factors. Significant main effects and
183 interactions were investigated with a Fisher least significant differences post hoc test. The
184 level of significance was set at $\alpha=0.05$.

185

186 **RESULTS**

187 **Clinical results:** At the time of data collection no clinical evidence of knee pain and effusion
188 was found in the ACL-reconstructed subjects. All subjects in the ACL-reconstructed group
189 were satisfied with the outcome of the surgery and resumed their pre-injury level of sports
190 participation. Negative Lachman and pivot-shift tests indicated that the knee joint stability
191 was regained clinically for all ACL-reconstructed subjects. For the subjects with ACL
192 reconstruction, the median Lysholm score was 95 (range 94-100) and the Tegner score was 8
193 (range 7-9) at the time of examination. KT-1000 results revealed that the mean difference
194 between the anterior tibial translation of the reconstructed and intact contra-lateral sides was
195 1.6 mm (range 1 to 2 mm) for the 134N test and 1.8 mm (range 1-2 mm) for the maximum
196 manual test, respectively.

197

198 **Physiological results:** Moderate intensity running was performed at an average intensity
199 63.9% (4.1) and 64.2% (4.6) of their predetermined $VO_2\max$ for the control and reconstructed

200 group respectively. Pre-exercise blood lactate values were 2.1 (0.3) and 2.1 (0.2) mM and
201 post-exercise blood lactate values averaged 2.3 (0.3) and 2.4 (0.6) mM for the control and
202 reconstructed group respectively. High intensity running was performed at an average
203 intensity 88.7% (3.1) and 87.6% (4.4) of their predetermined VO₂max for the control and
204 reconstructed group respectively. Pre-exercise blood lactate values were 2.1 (0.3) and 2.1
205 (0.3) mM and post-exercise blood lactate values averaged 7.9 (1.6) and 7.6 (1.7) mM for the
206 control and reconstructed group respectively.

207

208 **Electromyographic results:** During moderate intensity exercise there was a main effect of
209 muscle since significantly higher activity was found for VL compared to BF ($p<0.05$).
210 However this result will not be considered further since the EMG data were not normalized
211 (see below in Discussion section). There was not any other significant main effect or
212 interaction. EMG amplitude remained unchanged for all legs for both the VL and BF.

213 INSERT TABLE 1 ABOUT HERE

214 During high intensity exercise there was a main effect for muscle since significantly higher
215 EMG activity was found for VL compared to BF ($p<0.05$). However this result will also not
216 be considered further since the EMG data were not normalized. When comparing the control
217 and intact contra-lateral leg during high intensity exercise, we found a main effect for time
218 since EMG activity increased from the 3rd to 10th of exercise for both legs ($F=10.89$, $p<0.001$,
219 $\text{power}=0.99$) and a muscle* time interaction since EMG activity increased in time for the VL
220 but not for the BF ($F=4.48$, $p<0.01$, $\text{power}=0.87$). Furthermore when comparing the intact
221 contra-lateral with the reconstructed leg, we found a main effect for time ($F=7.96$, $p<0.001$,
222 $\text{power}=0.98$) since EMG activity increased between the 3rd and 10th minute of exercise and a
223 muscle*time*leg interaction ($F=3.36$, $p<0.05$, $\text{power}=0.72$) since EMG activity increased
224 between the 3rd and 10th minute for the VL of the intact leg while remained unchanged for the

225 VL of the reconstructed leg and increased between the 5th and 10th minute for the BF of the
226 reconstructed leg while remained unchanged for the BF of the intact contra-lateral leg. Finally
227 when comparing the control with the reconstructed leg, we found a main effect for time
228 (F=6.79, p<0.001, power=0.97) since EMG activity increased between the 3rd and 10th
229 minute of exercise and a muscle*time*groups interaction (F=3.03, p<0.05, power=0.70) since
230 EMG activity increased between the 3rd and 10th minute for the VL of the control group while
231 remained unchanged for the VL of the reconstructed group and increased between the 5th and
232 10th minute for the BF of the reconstructed group while remained unchanged for the BF of the
233 control group.

234 INSERT TABLE 2 ABOUT HERE

235

236 **DISCUSSION**

237 The purpose of the present study was to investigate the effect of ACL reconstruction on the
238 quadriceps-dominant strategy during moderate and high intensity running. We hypothesized
239 that (a) during moderate intensity exercise there will be no evidence of quadriceps-dominant
240 strategy for any of the control, intact contra-lateral and ACL-reconstructed leg, (b) during
241 high intensity exercise the quadriceps-dominant strategy will be evident for the control and
242 intact contra-lateral but not the ACL-reconstructed leg.

243

244 The first hypothesis was confirmed by our results. During 10 minutes of moderate intensity
245 running, the EMG amplitude of VL and BF remained unchanged with time for the control,
246 intact contra-lateral and reconstructed leg (TABLE 1). The second hypothesis was also
247 verified by our results. VL EMG activity increased for the control and intact contra-lateral but
248 not the reconstructed leg. Furthermore BF EMG activity showed an opposite trend and
249 increased for the reconstructed and not for the control or intact leg (TABLE 2). Collectively

250 we observed that during high intensity exercise the development of the quadriceps-dominant
251 strategy is evident for the control and intact contra-lateral but not the reconstructed leg.

252

253 Our results are in agreement with previous studies indicating that in individuals performing
254 moderate intensity exercise, EMG amplitude of the exercising muscles remains unchanged
255 with time [9, 10, 25, 26, 27]. Thus, our results verify that under low demand activities such as
256 moderate intensity running there is no presence of a quadriceps-dominant strategy in either
257 control or ACL- reconstructed athletes.

258

259 Regarding high intensity activities, previous studies indicate that fatiguing exercise is
260 associated with increased activation of the agonist muscles [8, 9, 10, 15, 16, 26, 27].

261 Concomitant with the increased agonist muscle activity there has been demonstrated unaltered
262 antagonist muscle activity [8, 15, 16]. This preferential increase in agonist activity during
263 high intensity exercise has been characterized as quadriceps-dominant strategy and is
264 considered to reflect the physiological response to the accumulation of metabolic fatigue [9,
265 10, 26, 27, 28] as well as a biomechanical consequence that is associated with better
266 neuromuscular control of the joint during fatigue [8, 15, 16]. Our results are in agreement
267 with the development of quadriceps-dominant strategy during fatiguing exercise showing that
268 both the control knee of uninjured athletes, as well as the intact contra-lateral knee of ACL-
269 reconstructed athletes, exhibit an increased EMG activity of the vastus lateralis muscle
270 concomitantly with unaltered biceps femoris activity. Thus, our results demonstrate that the
271 intact contra-lateral knee of an ACL-reconstructed patient shows the exact same
272 neuromuscular response with a “normal” knee during high intensity exercise. This suggests
273 that no compensations are observed on the intact contra-lateral side during high intensity
274 exercise regarding the response to accumulating fatigue.

275 Our results further demonstrated that the ACL-reconstructed leg deviated from the normal
276 quadriceps-dominant strategy showing no increase in VL activity coupled with increased BF
277 activity. This deviation from the quadriceps-dominant strategy pattern that was noted for the
278 control knees may reflect a “protective” mechanism in the case of ACL-reconstructed knees,
279 where the quadriceps-dominant strategy has been replaced by a “hamstrings-dominant”
280 strategy. This modification in the knee musculature activity during high intensity exercise,
281 leads to a decreased anterior stress applied to the ACL graft as compared to the corresponding
282 situation observed for control knees.

283

284 Our results may offer a reasonable explanation in certain cases of ACL re-injury after a
285 unilateral ACL reconstruction. We believe that the quadriceps dominant strategy per se can
286 not be responsible for contra-lateral injury since this strategy is the “normal” condition.
287 Reconstructed subjects are more prone to (re)-injury compared to controls because their
288 previous injury [29]. However within the reconstructed group there is a neuromuscular
289 “asymmetry” with one leg demonstrating quadriceps dominant-strategy and the other one a
290 more “knee-protective” hamstring-dominant strategy. Thus the intact contra-lateral leg has
291 theoretically greater risk for injury compared to the operated leg. This neuromuscular
292 “asymmetry” may offer a possible explanation in the case of contra-lateral injuries but in
293 cases of re-ruptures/graft failures other mechanisms must be considered. Although there is
294 controversy in the literature regarding the exact incidence rates for contralateral ACL rupture
295 and for re-rupture/graft failure after a unilateral ACL reconstruction [30, 31, 32, 33], these
296 situations are both significant issues, especially for young athletic and active population after
297 the index operation. In addition, since previous studies have noted that the incidence of injury
298 to the contralateral intact knee after unilateral ACL reconstruction is associated with higher

299 activity level [30, 31, 33], our results may have special clinical value, by offering a potential
300 explanatory mechanism for such injuries at high intensity exercise.

301

302 Several explanations can be offered for the absence of the quadriceps-dominant strategy at the
303 ACL-reconstructed knee. These include selective muscle fiber atrophy in the involved
304 quadriceps [1, 2], altered motor unit activation following surgery and subsequent retraining
305 [3] and loss of joint afferent information which may lead to suboptimal muscle fiber
306 activation [4]. These neuromuscular alterations following ACL reconstruction may be
307 responsible for the unaltered agonist EMG activity during high intensity exercise. Regarding
308 antagonist EMG activity, increased BF EMG activity has been shown in ACL deficient
309 subjects during low demand activity, such as walking and jogging [12, 13, 34, 35], but
310 surgical reconstruction seems to re-establish biceps femoris activity towards normative values
311 under non-fatiguing activities [12, 13, 14]. This was also verified in the present study showing
312 unaltered BF activity during the moderate intensity running. Thus the increased BF activity
313 following ACL reconstruction is only evident during high intensity fatiguing exercise.

314

315 The reason for the increased antagonist EMG activity in the reconstructed leg is not clear
316 from the present study. Interestingly the activation ratio in the reconstructed leg has shifted
317 towards the antagonist (biceps femoris) and this may “mimic” the quadriceps avoidance gait
318 pattern seen in ACL deficient subjects [36, 37]. Furthermore the reciprocal activation pattern
319 seen in the control and intact contra-lateral leg [38] is no longer present and this may favour
320 increased antagonist activity.

321

322 To the best of our knowledge this is the first study that investigated EMG activation patterns
323 during intense exercise in ACL reconstructed athletes. Previous studies on ACL reconstructed

324 athletes have compared EMG levels under moderate intensity activities and no study has
325 investigated EMG activity with time during high intensity activities [11, 13, 14]. Our
326 approach enabled us to extend our findings to intense running which represents a highly
327 functional activity for the ACL reconstructed athlete. Furthermore ACL injuries and re-
328 injuries are common during high intensity exercise [39, 40] and thus low demand activities
329 such as walking or light jogging may have limited value regarding the efficiency of the
330 neuromuscular function following ACL reconstruction. Strength of this study was that by
331 monitoring cardiorespiratory data we were able to assign the subjects exercised at a
332 comparable level. Pre- and post- exercise measurements of blood lactate demonstrated that
333 lactate was not significantly elevated, further demonstrating the mild physiological strain
334 imposed on the subjects during the moderate intensity exercise. Similarly, our
335 cardiorespiratory data indicated that both our groups exercised at a comparable high fraction
336 of their VO_2max during high intensity exercise bouts. Blood lactate values increased from
337 baseline ($\sim 2\text{mM}$) to a similar high level ($\sim 7\text{-}8\text{mM}$) indicating the accumulation of significant
338 metabolic fatigue. Thus we are confident that similar levels of fatigue occurred in our groups
339 and that the presence of the quadriceps-dominant strategy is a consequence of fatigue
340 accumulation.

341

342 Our study has some limitations. Our sample consisted of male patients with BPTB graft
343 which does not allow for generalization of our findings to female patients. Also, since no data
344 for the ACL-deficient knee were collected it is not clear whether the data observed in the
345 ACL-reconstructed knee is secondary change after surgery or preexisting abnormality caused
346 by ACL deficiency. It should also be acknowledged that EMG recordings should be
347 performed with great care and the results should be interpreted with caution during dynamic
348 muscle contractions. Signal capturing, recording and processing was performed according to

349 established guidelines [22, 23, 41]. We examined EMG activity developed solely during the
350 stance period, thereby reducing to some extent the role of the signal non-stationarities with
351 respect to other effects being studied [41]. Furthermore, the activity of many (successive)
352 steps was averaged providing a reasonable estimation of peak EMG amplitude. Normalisation
353 of EMG data (for example to maximum voluntary contraction) was not performed due to the
354 additional error introduced by this process and the fact that our study design involved
355 repeated measures, thereby overcoming influences of electrode positioning and inter-
356 electroded distance on the signal value [42]. We assumed that because the same
357 instrumentation was use for all subjects, the level of measurement noise would be consistent
358 for all subjects and that any differences could be attributed to changes within the system itself.
359 Finally our dependent variable was examined across a “control” condition (moderate exercise)
360 as well as two “control” legs (control and intact contra-lateral).

361

362 **Conclusions:**

363 There is no presence of a quadriceps-dominant strategy in the ACL reconstructed athletes
364 during moderate intensity exercise. During high intensity exercise, the intact contra-lateral leg
365 develops a quadriceps-dominant strategy, whereas the ACL-reconstructed leg does not. The
366 reconstructed leg increases instead biceps femoris activity, developing a “hamstring-
367 dominant” strategy and this “asymmetry” may theoretically be in favor of the reconstructed
368 knee.

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496 **FIGURE LEGENDS**

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498 **FIGURE 1:** Bilateral recording for a representative ACL reconstructed subject during high
499 intensity running. Vertical lines indicate right footswitch. The time between heel strike and
500 toe-off corresponds to the stance phase.

501 **TABLE 1.** Main effects and interactions during moderate intensity exercise (n=14).

	CON vs. REC				CON vs. INT				INT vs. REC		
	F	p	power		F	p	power		F	p	power
	ratio	value			ratio	value			ratio	value	
muscle	24.9	<0.001	0.99	muscle	26.64	<0.001	0.99	muscle	9.594	0.008	0.91
groups	1.24	0.276	0.46	groups	0.03	0.854	0.12	leg	1.39	0.286	0.33
time	1.71	0.171	0.29	time	0.15	0.926	0.09	time	0.133	0.94	0.12
muscle*groups	3.3	0.081	0.48	muscle*groups	2.57	0.121	0.22	muscle*leg	0.039	0.847	0.22
muscle*time	0.36	0.779	0.23	muscle*time	1.03	0.386	0.15	muscle*time	1.13	0.351	0.35
time*groups	0.7	0.554	0.16	time*groups	1.38	0.256	0.28	leg*time	0.87	0.467	0.19
muscle*time*groups	1.73	0.168	0.31	muscle*time*groups	0.88	0.455	0.17	muscle*leg*time	0.375	0.771	0.23

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503 F ratios, p values and the corresponding power for every main effect and interaction during the moderate intensity exercise.

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508 **TABLE 2.** Main effects and interactions during high intensity exercise (n=14).

	CON vs. REC				CON vs. INT				INT vs. REC		
	F	p	power		F	p	power		F	p	power
	ratio	value		ratio	value		ratio	value			
muscle	13.641	<0.001	0.95	muscle	27.122	<0.001	0.99	muscle	6.26	0.026	0.64
groups	0.39	0.537	0.148	groups	0.02	0.879	0.07	leg	0.799	0.39	0.13
time	6.79	<0.001	0.97	time	10.89	<0.001	0.99	time	7.96	0.001	0.98
muscle*groups	3.81	0.062	0.47	muscle*groups	0.947	0.34	0.16	muscle*leg	1.131	0.31	0.17
muscle*time	0.63	0.6	0.176	muscle*time	4.48	0.006	0.87	muscle*time	0.189	0.903	0.08
time*groups	3.32	0.024	0.74	time*groups	1.44	0.239	0.37	leg*time	4.76	0.006	0.87
muscle*time*groups	3.03	0.034	0.70	muscle*time*groups	0.662	0.58	0.18	muscle*leg*time	3.36	0.028	0.72

509

510 F ratios, p values and the corresponding power for every main effect and interaction during the high intensity exercise.

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