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ACL deficiency influences medio-lateral tibial alignment and knee varus-valgus during in vivo activities

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# ACL deficiency influences medio-lateral tibial alignment and knee varus\_-valgus during in\_-vivo activities

#### 4 Abstract

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Purpose: The role of the anterior cruciate ligament (ACL) in
knee biomechanics in vivo and under weight-bearing is still
unclear. The purpose\_of\_this\_study\_was\_to\_compare\_the
tibiofemoral kinematics of ACL\_-deficient knees to healthy
contralateral ones during the execution of weight-bearing
activities.

Methods: Eight patients with isolated ACL injury and healthy contralateral knees were included in the study. Patients were asked to perform a single step forward and a single leg squat first with the injured knee and then with the contralateral one. Knee motion was determined using a

validated model-based tracking process that matched
subject-specific MRI bone models to dynamic biplane
radiographic images, under the principles of Roentgen
stereophotogrammetric analysis (RSA). Data processing was
performed in a specific software developed in Matlab.

**Results:** Statistically significant differences (p < 0.05) were 21 found for single leg squat along the frontal plane: ACL-22 deficient knees showed a more varus angle, especially at the 23 highest knee flexion angles (40-50° on average), compared 24 to the contralateral knees. Furthermore, ACL-deficient knees 25 showed tibial medialization along the entire task, while 26 contralateral knees were always laterally aligned. This 27 difference became statistically relevant (p<0.05) for knee 28 flexion angles included between  $0^{\circ}$  and about  $30^{\circ}$ . 29

Conclusion: ACL--deficient knees showed an abnormal 30 tibial medialization and increased varus angle during single 31 leg squat when compared to the contralateral knees. These 32 biomechanical anomalies could cause a different force 33 distribution on tibial plateau, explaining the higher risk of 34 early osteoarthritis in ACL deficiency. The clinical relevance 35 of this study is that also safe activities used in ACL 36 rehabilitation protocols are significantly altered in ACL 37 deficiency. 38

39 Level of evidence: Level III

Keywords: Anterior cruciate ligament, Knee kinematics, In
vivo, Single leg squat, Biplane radiography

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## 64 Introduction

The role of anterior cruciate ligament (ACL) in knee 65 kinematics has been largely investigated. ACL function as a 66 primary restrain of the anterior tibial displacement in static 67 conditions is widely accepted, like its probable role in acting 68 like a secondary restraint of internal tibial rotation [1, 5, 8– 69 11, 17–19, 24, 31]. The relevance of biomechanical studies 70 importance of their constant technological and the 71 improvement derives from the necessity of a better 72 comprehension of mechanisms that lead to an improved risk 73 of osteoarthritis in patients affected by ACL deficiency [1, 2, 74 5, 6, 9, 10, 14, 18, 23, 33]. 75

In particular, the comprehension of how the lack of ACL
modifies knee biomechanics not only in vivo and
dynamically, but also under weight-bearing conditions, is

<sup>79</sup> crucial to gain information as close as possible to what
<sup>80</sup> happens in daily life motion.

Motion capture tools such as video- analysis and 81 radiostereometry are valuable tools to understand better the 82 biomechanics of the knee during common movements of 83 daily and sport activities [1, 5, 8-10, 15, 18, 26, 33]. The 84 main limits of these methods are related to their accuracy, 85 because reconstruction of joint kinematics is based on skins 86 sensors, which are affected by relevant artifacts. Double 87 fluoroscopy overcomes the previous problem, because it 88 studying directly allows bone movements through 89 radiographs' exposition of patients executing motor tasks [3, 90 4, 6, 14, 29, 33]. In this scenario, joints biomechanical 91 following anomalies pathologies distinct could be 92 investigated in a more accurate way, thanks to dynamic 93

Roentgen stereophotogrammetric analysis (RSA) [3, 4]. 94 Biomechanical differences between the anterior cruciate 95 ligament-deficient (ACLD) knees and contralateral of the 96 subjects could be identified using a biplane same 97 radiographic system. In the present study, gait and single leg 98 squat were analyzed, since the first one is a basic activity of 99 daily living and the second one is a more demanding motor 100 task, but safe and easy to perform for the patients [17, 31]. 101 The aim of the present study was to identify knee 102 biomechanical anomalies following ACL rupture, during the 103 execution of in vivo under weight-bearing activities, to 104 investigate mechanisms that lead to improved risk of 105 osteoarthritis in ACL deficiency. 106

It was hypothesized that knee tibiofemoral kinematics is
altered after ACL tear and that the alteration probably does

not involve only anterior posterior laxity or internal\_\_\_\_\_
external rotation, but also flexion\_\_\_extension and mediolateral tibial alignment, <u>as</u> previously reported by other
investigators [1, 5, 9, 15, 18, 19].

The clinical relevance of this work is that proving a 113 significant impairment and altered patterns in gait kinematics 114 could support a wider recourse to surgery, because walking 115 is a basilar activity and its constant alteration could influence 116 knee degeneration more than sport activities, which most of 117 the people do occasionally. Moreover, an altered knee 118 kinematics in single leg squat could confirm the necessity of 119 surgery for athletes. 120

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#### 122 Materials and methods

All the patients involved in this research study signed 123 informed consent forms. This study obtained the approval 124 from the Institutional Review Board (IRB) of Rizzoli 125 Orthopaedic Institute (ID: 40/CE/US/ml-Clinical Trial 126 Gov ID: NCT02323386). This study represents the 127 secondary analysis of data collected from a prospective 128 study, aimed to evaluate the outcome of ACL reconstruction. 129 Based on the original study protocol, 62 patients were 130 included and assessed preoperatively with 1.5 T MRI 131 analysis and dynamic RSA of injured and contralateral knee. 132 The inclusion criteria for the original study were: 133

- <sup>134</sup> Age 16–50 years.
- Complete, traumatic and unilateral ACL injury.
- No previous knee ligament reconstruction or repair.

137	- No concomitant posterior cruciate ligament, postero-
138	lateral corner, lateral collateral ligament or medial
139	collateral ligament lesion.
140	- Absence of mild or advanced knee osteoarthritis
141	(Kellgren–Lawrence III–IV)
142	For the purpose of the present study, the inclusion criteria
143	were:
144	- Isolated ACL tear.
145	- No injury of contralateral knee
146	Exclusion criteria were:
147	- Concomitant other ligamentous or meniscal injuries.
148	- Incomplete kinematic data
149	- Unwillingness to take part in the study.
150	From the 62 patients of the initial cohort, 10 patients
151	underwent dynamic RSA of the contralateral knee. Two

more patients were then excluded because of incomplete kinematic data. Overall, <u>eight</u> patients (5 men, 3 women, 30  $\pm$  12 years old) matched the inclusion criteria and were included in the study.

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#### 157 *Motor tasks*

The patients were asked to perform two motor tasks: a single 158 step and a single leg squat. The tasks were performed with 159 the ACLD limb and subsequently with the contralateral one. 160 Patients were asked to perform the tasks according to their 161 possibilities. The investigators carefully checked the initial 162 position of the foot to limit the bias caused by 163 internal—external alignment: the foot had to be aligned with 164 the ideal antero-posterior axis of the knee, thus pointing 165 forward. The acquisition was performed in a specialized 166

radiographic room. The tasks were performed <u>three</u> times
per limb, the first two to gain comfort with the experimental
set-up (no X-ray exposure) and the third one for data
acquisition (X-ray exposure).

171

#### 172 Data acquisition

The data were collected using a radiographic set-up for
dynamic RSA. The device used (BI-STAND DRX 2) was
developed in our institute, in collaboration with ASSING
(ASSING Group, Rome, Italy). The specifics of the RSA
radiographic set-up were -analogous to the ones already
published in previous articles from the same study group [3,
4] (Figure 1A).

Bone models of tibia and femur were obtained from a 1.5T
MRI of either the affected or the contralateral knee. When

MRI images of the contralateral knees were not available, the 182 models were derived from a process of mirroring of the ones 183 of the affected knee and of their correspondent reference 184 systems. The radiographic images were processed in a 185 dedicated software in Matlab® (R2016a, MathWorks Inc., 186 Natik, MA, USA) developed at our institute, applying 187 algorithms related to the Model-Based Dynamic RSA. A 3D 188 virtual environment used for semi-automatic was 189 segmentation of bone contours on radiographic images 190 and, subsequently, to place the bone models according to the 191 contours (Figure 1B). 192

The <u>dynamic RSA</u> was validated before to start the clinical
study. The validation protocol was based on radiograph
computer simulations of the radiological setup and images,
with different quality and noise level. The accuracy of the

radiological scene reconstruction and of the model position 197 was assessed according to the ISO-5725 regulation [34]. The 198 global accuracy of model positioning and orientation, 199 evaluated in terms of "trueness  $\pm$  precision", resulted to be 200 sub-millimetric, respectively,  $0.22 \pm 0.46$  mm and  $0.26 \pm 0.2$ 201 °. Kinematics data are presented as mean  $\pm$  standard error 202 over the percentage of the task. Figure 2 shows the reference 203 systems of the tibial and femoral models in the RSA 204 software. The kinematical quantitative data for each patient, 205 206 in 6 degrees-\_of -freedom, were calculated using the Grood and Suntay decomposition [13]. 207

Since it was impossible to standardize the time elapsed to perform the motor task by each patient, we normalized the data on the percentage of the task (% task), based on specific moments to determine the beginning, the middle and the end 212 (Table 1). Regarding the gait, only the stance phase was213 taken into account.

## 215 Statistical analysis

The kinematic data were processed using Matlab. The paired t- test was used to compare the data of the ACLD an contralateral knees along each frame of the entire motor task for all the parameters. Differences were considered statistically significant for p<0.05.

An a-\_priori power analysis was conducted, based on 221 previous studies using fluoroscopic technique to evaluate 222 kinematics ACLD conditions knee in [6, 29, 30]. 223 Considering a medio-lateral translation of  $2.51 \pm 1.30 \text{ mm}$ 224 for ACLD knee and of  $0.89 \pm 1.47$  mm for contralateral knee, 225

<sup>214</sup> 

to achieve a power of 0.8 and an alpha level of 0.05, the minimum number of patients required was set to seven.

## 229 **Results**

#### 230 Frontal plane

Regarding the joint angles and translations on the frontal 231 plane, there were statistically significant differences between 232 ACLD and contralateral knee (p<0.05) (Table 2). In 233 particular, varus—valgus rotations were statistically different 234 from the 50% to the 80% of the squat (Figure 3B): ACLD 235 knee showed, on average, a more varus rotation compared to 236 the contralateral knee. Furthermore, medio-lateral 237 translations showed a more medial tibial alignment for 238 ACLD knees with respect to the frontal plane. This trend was 239 present both in the squat and in the step (Figs. 3A, 240

4): in the squat, the difference was statistically
significant from 0% to 35% and from 65% to 100% of the
task; no statistical differences were found in the step.

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#### 245 Sagittal and transverse plane

Regarding sagittal and transverse plane joint angles and
translation, no statistical differences were found between
ACLD and contralateral knee kinematics along the entire
percentage of both motor tasks (n.s.).

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#### 251 **Discussion**

<sup>252</sup> The main findings of the present study were:

Statistically significant differences were found —in
 medio-lateral translations between ACL\_-deficient and
 contralateral knees during single leg squat from 0% to

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35% and from 75% to 100% of the motor task (that correspond to an average flexion value from  $0^{\circ}$  to  $30^{\circ}$ ); -• During single leg squat, significant differences were found in varus-valgus angle from 50% to 80% of motor task;-

• No differences were observed between afflicted and contralateral knee during the stance phase of the gait. he influence of ACL deficiency on knee kinematics is a hot opic in recent orthopedic researches, due to the orrelation altered biomechanics is supposed to have with ncreased risk of early osteoarthritis [1, 2, 5, 6, 9, 10, 14, 18, 3, 33]. To the best of our knowledge, this is one of the first studies aimed to analyze, with an advanced and highly 268 accurate technology, the translations and rotations of ACLD 269 and contralateral knee joint in vivo and under weight-bearing 270

conditions. On purpose, two tasks that differed in terms of
closed (squat) and open (step) kinetic chain were analyzed.
Onthe one hand, gait is one of the commonest daily
activities, easily performed by ACLD patients too. On the
other hand, the squat was chosen since it is more demanding
but, <u>at the same time</u>-safe to perform [17,
31].

Other investigators have already observed the concept of 278 tibial medialization (Figure 5) after ACL injury, inferring 279 this is due to the oblique orientation of ACL. Li et al. [18], 280 analyzsed single leg weight-bearing lunge through double 281 fluoroscopy and found a significant lateral shift of tibio-282 femoral cartilage contact points, both in the medial (between 283  $0^{\circ}$  and  $60^{\circ}$  of flexion) and the lateral compartment of the tibia 284 (between  $15^{\circ}$  and  $30^{\circ}$  of flexion). This finding was 285

reproduced also in a cadaveric study [19], where the 286 application of different loading conditions in specimens with 287 ACLD knee led to a significant tibial medialization between 288 15° and 30° of flexion. Furthermore, DeFrate et al. [5] found 289 a greater tibia medialization in ACLD knees from  $0^{\circ}$  to  $90^{\circ}$ 290 of flexion during the execution of a quasi-static lunge. These 291 results are in accordance with the findings of the present 292 study, since a significant tibial medialization was observed 293 in correspondence to a knee range of flexion between  $0^\circ$  and 294 30°. This abnormal position could explain the high incidence 295 of osteoarthritis on the medial femoral condyle and anterior 296 tibial spine in chronic ACL deficiency [7, 23]: medial shift 297 of the tibia could reduce the distance between these two knee 298 structures, leading to an altered force distribution on their 299 surfaces [18]. 300

The contribution of ACL in varus-valgus laxity is also a 301 controversial topic [12, 22, 29, 32]. In the present study, 302 ACLD knees were found significantly more varus than the 803 contralateral ones in the first degrees of the re-extension 304 phase of the squat, after they reach the maximum flexion. A 305 crucial role of ACL in frontal plane knee rotations can 306 therefore be supposed. Previous literature studies drew the 307 same conclusion. Yamazaky et al. [32] demonstrated ACL 308 injured limbs had a more knee varus than uninjured of about 309  $5^{\circ}$  at the maximum flexion angle of a single leg squat, using 310 an electromagnetic device. In another study [29], performed 311 with fluoroscopy, knees after ACL reconstruction were 312 shown to be more varus than contralateral during downhill 313 running. This aspect could endorse the surgical techniques' 314 inability to restore physiologic knee varus-valgus after 815

ACL tear. Lastly, there is the recent concept of valgus collapse as <u>a</u>\_frequent mechanism involved in ACL noncontact injury [25], which could bring to suppose knee valgus as a position of discomfort for patients simulating the ligament rupture biomechanics. ACL-injured patients could probably maintain an easier balance keeping a more varus position [32].

Differently than expected, no differences were found neither 323 in tibial anterior—posterior translation <del>nor</del> in knee internal— 324 external rotation. Closed kinetic chain exercises like squat 325 are considered safer than open kinetic chain ones in ACL 326 injury rehabilitation programs, especially when patients need 327 to increase muscle activity, because they are supposed to 328 cause less ligament strain [20]. For this reason, squat 329 exercises have a role in ACL deficiency rehabilitation: the 330

high muscular co-activation of quadriceps and hamstrings 331 provides a greater anterior—posterior tibial stability [17, 31]. 332 This consideration could justify the absence of differences in 333 tibial position in anterior-posterior knee laxity and in 834 internal-external rotation in our data. Moreover, some 335 previous studies described a higher tibial internal rotation in 336 ACLD knees, but for motor task different from the squat [5, 337 10]. 338

In step, we did not found any statistical difference between ACLD knee kinematics and contralateral one. These results are partially in contrast with literature: several studies [9, 15] identified anomalies in knee flexion—extension during walking, but showed neither significantly more anterior tibial translation nor an increased antero-posterior laxity range. Gao et al. [9] described an increased tendency of the

ACLD knees to remain in flexion at the end of the stance 346 phase of the gait, while Hurd and Snyder-Mackler [15] 347 described a "joint stiffness strategy" as a combination of 348 reduced peak knee flexion and lack of extension during the 349 mid-stance. The main thesis for this altered knee flexion 350 pattern relies on abnormal muscle activation in patients 851 with ACL tear, aimed to better control knee anterior-352 posterior laxity. Indeed, many studies based on 353 electromyography highlighted differences in activation of 354 quadriceps and hamstrings after ACL injury, even if there is 355 no consensus regarding the adaptation mechanism [15, 26, 356 27]. 357

In the present study, no flexion\_-extension anomalies were identified. The step was executed at a low speed and usually with small step length. Previous investigators demonstrated

that small spatiotemporal parameters influence knee flexion
 during stance, thus resulting in a stiff knee strategy [21, 28]
 and an almost full extension, <u>similar to</u> our results.

In brief, the findings of the present study could indicate 364 on top of the role of ACL in knee biomechanics: in vivo and 365 under weight-bearing conditions, the ACL could decisively 366 contribute to medio-lateral tibial alignment and knee varus-367 -valgus. So far, the ACL reconstruction techniques have 368 focused on the restoration of anterior-posterior 369 and internal-external rotation knee stability, without 870 considering the anomalies on frontal plane. Actually, 371 previous studies reported that ACL reconstruction does not 372 restore these parameters [6, 29]. According to the present 373 study, surgeons should observe ACL injury from a wider 374 perspective, thus considering also ACLD knee motion 375

anomalies in the frontal plane, to develop reconstruction 376 techniques aimed to reproduce physiological knee stability. 377 The present study has several limitations. First, due to the 378 controlled nature of the tasks (especially the step), the small 379 sample size could have affected the statistical analysis and 380 probably failed to reveal other differences between the two 381 groups. However, it was possible to demonstrate some 382 consistent trends. A second, intrinsic limitation linked to the 383 sample size relied upon the high intra-subject knee motion 384 The choice to variability. acquire, under radiograph 385 exposure, only one repetition per task, was made due to 386 ethical reasons. This issue was minimized through a direct 387 comparison of healthy and unhealthy limbs of the same 388 patients. 389

The other two considerations include the selection of 390 patients based on time from injury and the choice of 391 contralateral limbs as gold standard. When debating on 392 ACL--deficient knee biomechanics, the time from injury is 393 patients crucial, because may progressively develop 394 muscular asymmetries to stabilize the joint [33]. 395 Nevertheless, the present study was mainly focused on how 396 the injury affected the biomechanics and not on how 397 rehabilitation could restore knee stability. The contralateral 398 knees might not reproduce a normal knee kinematics [16]. 399 Anyhow, obtaining a pool of healthy controls would have 400

<sup>401</sup> been highly unethical due to radiograph exposure;
<sup>402</sup> furthermore, the evaluation of contralateral knees as controls
<sup>403</sup> is typical of nearly all the fluoroscopic studies.

Lastly, the choice of the tasks was related to the actual 404 radiographic set-up: due to the limited spaces and the 405 obstacles represented by the medical devices around, it 406 would have been unsafe and impossible to analyze high-407 dynamics tasks, such as jumps or cut\_-maneuvers. 408 These last tasks could have stressed the knee joint more, and 409 maybe underlined further differences from the contralateral. 410 A future set-up development will permit -acquire more 411 complex and stressing tasks. 412

413

#### 414 **Conclusion**

ACL\_\_\_\_\_deficient knees showed an abnormal tibial medialization and increased varus angle compared to the contralateral knees. These biomechanical anomalies may lead to different forces distributions on the tibial plateau,

419	explaining the higher risk of early osteoarthritis in ACL
420	deficiency. Clinicians should take into account the influence
421	of ACL tear on frontal plane knee kinematics in movement
422	commonly used in ACL rehabilitation protocols.

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427

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## 601 Figures Legend

**Figure 1** Radiological set-up of <u>the RSA</u> device, where patients performed motor tasks. The orthogonal arrangement of flat panels and X-ray tubes allows a 3D reconstruction of bones movements (A); <u>v</u>Virtual reconstruction of a motor task in the RSA software, where mathematical data describing tibio-femoral kinematics were extrapolated (B). **Figure 2** Anatomical reference systems of tibia and femur in <u>the RSA software. X-axis: flexion angle and the medio-</u> lateral translation; Y-axis: varus—valgus rotation and anterior—posterior translations; Z-axis: internal—external rotations and proximal—distal translation.

Figure 3 Medio-lateral translations (mean ± SEM) of the 613 tibia with respect to the femur during single leg squat; notice 614 that significant differences were found from 0% to 35% and 615 from 75% to 100% of the motor task (that correspond to an 616 average flexion value from  $0^{\circ}$  to  $30^{\circ}$ ) (A). Varus-valgus 617 rotations (mean  $\pm$  SEM) of the tibia with respect to the femur 618 during single leg squat; notice that significant differences 619 were found from 50% to 80% of the motor task (B). 620

Figure 4 Medio-lateral translations (mean  $\pm$  SEM) of the tibia with respect to the femur during the stance phase of the gait; notice that, despite no significant differences <u>beingwere</u>
found, the tibias of ACLD knees were on average shifted to
a more medial position than <u>the</u> ones of <u>the</u> contralateral
knees.

Figure 5 Difference in medio-lateral tibial position between the normal knee (A) and the ACL-deficient knee (B).

## 630 Tables

Motor task normalization						
Time percentage	Phase of the step	Phase of the squat				
0%	Heelstrike	Initial extension				
50%	Midstance	Maximum flexion				
100%	Heeloff	Terminal extension				

631 Table 1 - List and value of the specific moments used to

632 normalize the data for the execution of the motor tasks.

Significant differences								
	% of the task	Injured	Contralatera l	p value				
Squat	0 - 35 %	$1.4\pm0.4$	$-1.2 \pm 0.7$	< 0.05				
medio- lateral translation s (mm)	65 - 100 %	1.5 ± 0.6	-1.9 ± 0.9	< 0.001				

Squat varus_ valgus angles (°)	50 - 80 %	-0.9 ± 1.3	-5.3 ± 2.2	< 0.05
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Table 2: <u>A</u>average  $\pm$  standard error values of the

significant differences between ACL- deficient and

636 contralateral knee

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## 639 List of abbreviations

- 640 ACL Anterior cruciate ligament
- 641 **ACLD** Anterior cruciate ligament deficient
- 642 **RSA** Roentgen stereophotogrammetric analysis