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Anthropometry of the cruciate ligaments of the knee: MRI study of the human four-bar linkage device

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SUMMARY

The knee acts as a functional unit whose stability depends on the equilibrium of its constituents. The set formed by the cruciate ligaments (CL), the femoral condyles and the tibial plateau, could be understood as a functional unit with a central pivot called the four-bar linkage. The union of the insertion sites of both CL reproduces a crossed union device of four three-dimensional bars that mimic the kinematic behaviour of the knee. The relationship between the femoral and tibial insertions of the anterior and posterior cruciate ligaments (ACL and PCL) is a constant value to be determined in the healthy human population. We included 200 magnetic resonance images (MRI) of healthy knees and measured real distances between the insertion points in the tibia and femur of both CL. We processed these data using the Cruliant-ETSIB® program to show the dimensions of each bar in full scale. We determined absolute variables: ACL, PCL, the distance between tibial insertions (TIDI) and the distance between femoral insertions (FEDI). We measured relative variables as well: TIDI/PCL, FEDI/PCL, PCL/ACL, TIDI/FEDI. There is a human proportion in healthy knees defined by the quotient TIDI/FEDI whose value is 1,45. The use of this quotient is proposed as a reference to optimise the location of the tibial and femoral insertions during reconstructive ligament surgery of the CL, as well as to assess the success of the reconstruction.

Key words: Cruciate ligaments – Knee – MRI – Four bar linkage – Insertion

INTRODUCTION

The ACL originates at the posterior area of the medial surface of the lateral femoral condyle and is inserted in the tibial plateau in the anterior intercondylar fossa, between the lateral and medial tibial tubercle (Petersen et al., 2006). The mean intra-articular length of the ACL is 32 mm (range 22-41 mm) (Kennedy et al., 1974; Trent et al., 1976). The PCL originates at the lateral surface of the medial femoral condyle, and it is anatomically anterior to the femoral insertion of the ACL (Harner et al., 1995). Its mean length is 32-38 mm (Kennedy et al., 1967).

The knowledge of the CL biomechanics is important in order to understand its role in the kinematics of the knee. The native CL maintain an almost uniform tension throughout the movement (Fu et al., 1999). The concept of isometry, which means a constant length between the two ends of their insertion during the range of movement, is an experimental concept more than an anatomical reality (Lavallée et al., 1994). Although the first bibliographical data point out the existence of an "isometric fibre" in the ACL (Odensten et al., 1985), several authors warned that functionally it cannot be considered as one (Schutzer et al.,

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1989; Dorlot et al., 1984), and biomechanically it is accepted that neither the ACL nor the PCL are strictly isometric (Furia et al., 1997). There is an "isometric behaviour" (Musalh et al., 2005) by which variations of 2 to 3 mm in the length of the CL are considered as normal, and they do not affect its function. There is not an agreement in the literature regarding the isometric tibial and femoral insertions of the CL (Sapega et al., 1990; Sidles et al. 1988; Penner et al., 1988; Melhorn et al., 1987; Friedrich et al., 1990; Hefzy et al., 1989; Bradley et al., 1988; Zavras et al., 2001), which has led to define insertion areas in which the ligament fibres experience changes of less than 2 mm with movement: isometric maps (Niitsu et al., 1996).

This experimental model has its practical application in the area of CL reconstructive surgery, which seeks to reproduce the native isometric conditions in order to minimise the lengthening of the grafts (Hutchinson et al., 2001), protecting the implant and increasing its survival. The objective of the CL reconstructive surgery is to seek the so-called anatometric positioning of the graft (Plaweski et al., 2011). It seeks an isometric reconstruction (constant intra-articular distance of the plasty) and anatomical reconstruction (on its anatomical original footprint), so that the implant behaves isometrically, is functional and avoids a conflict with the intercondylar notch (Odensten et al., 1985; Trent et al., 1976; Sapega et al., 1990; Sakane et al., 1997; Schindler, 2012).

Different methods and references appear in the literature to describe the original insertions of the CL: anatomical (bidimensional measuring of the distance from the centre of the ligament to specific anatomical points) or radiological (adapting references used to locate the tunnels in the reconstructive plasties for the original ligaments: "clock method" and the "quadrant method" (Bernard et al., 1997) in the femur; Staubli and Rausching (Staubli et al., 1994) and Amis and Jakob lines (Amis et al., 1998) for the tibia). It is, nonetheless, a simplification that obviates the tridimensionality of their insertions (Martins et al., 2012). Thanks to the development of 3D imaging techniques and technologies based on navigation, plus the growing interest in the bifascicular reconstructive techniques, the original anatomic insertion footprints of the ACL have been redefined (Hoshino et al., 2012).

The anatomy of the CL cannot be understood only in an isolated way. On the contrary, the concept of "central pivot" is basic either for understanding the biomechanical work of the knee and for any subsequent reconstructive approach. The set formed by the CL, the femoral condyles and the tibial plateau recreates a pattern whose activity makes it possible for the articular mobility on the one hand and, on the other, to maintain a certain articular restriction role, halting, in turn, certain forces. To simplify this relationship system, a theoretical model was developed: "four-bar linkage system". This mechanism is formed by four bars or links: two osseous links that join the insertions of the CL in the tibia and in the femur, and two ligamentous links that represent the CL. The first two bars represent the linear distance between the insertions of the CL in the sagittal plane of the femur (FEDI) and in the tibia (TIDI). The ligament bars represent the neutral fibres of the ACL and PCL, simplifying them as a single rigid bar with a single osseous insertion point, and assuming that this fibre remains in constant (isometric) length during the arch of movement. The intersection between the ACL and PCL bars represents the centre of instantaneous rotation of the joint. It is a characteristic point of each four-bar system, and its position in the space changes with the movement of the knee.

Zuppinger designed this system at the beginning of the 20th century as a model to represent the relationship between the CL during movement, and it has been the basis of numerous subsequent studies. Later Bradley proposed using a similar model as a tool to predict changes in the length of the plasties in reconstructive surgery. He tried to reflect the ligamentous functional unit of the knee in the sagittal plane. The "four-bar linkage" mechanism is a bidimensional model with two degrees of liberty (flexo-extension and rolling), which studies the interaction of the CL with the femorotibial joint.

In order to explain the functional and biomechanical behaviour of the knee, three dimensional models are needed. In the bibliographical review performed, we found only scant data regarding size of the femoral and tibial linkage bars of the CL. Bradley and O'Connor measured these distances using radiographic images from cadaveric knees, with

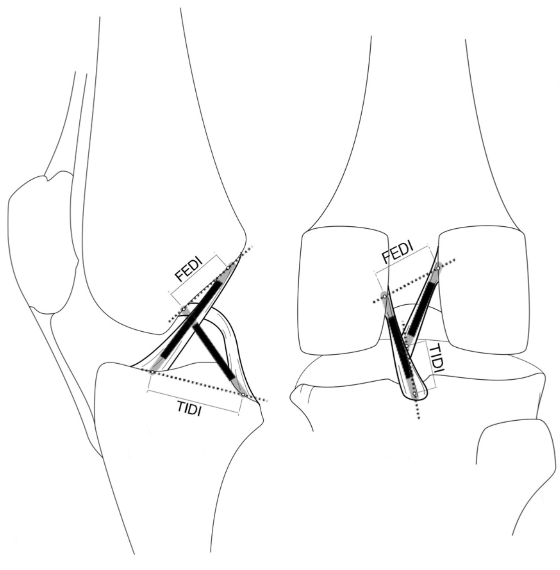

Fig. 1. Three-dimensional recreation of the four-bar system in the knee showing TIDI and FEDI in a sagittal and coronal views.

the bar linkage system of the femur being 14.5 and 12.8 mm respectively, while the bar linkage system of the tibia was 30.5 mm in both studies. Using data obtained from MRI images and software (Cruliant ®), a three- dimensional recreation of the four-bar system (Fig. 1) reproduced for the first time in 2001 the real anatomical distances existing between the anatomical insertions of the CL, being the femoral bar linkage of 20.35 mm and the tibial one of 30.25 mm.

There is a theoretical supposition by which different devices (of constitutionally different persons in size) reproduce the same kinematic behaviour of the knee. The purpose of this work is to determine the constant value that shows the existing relationship in normal conditions, both in the femur and in the tibia, between the ACL and the PCL in the healthy population. This value could be used as a reference for the correct placement of the substitute plasties in the repairing surgery, and also as a tool to verify their location after surgery.

MATERIALS AND METHODS

Subjects

The study included 200 MRI of Spanish patients selected from a group of 347 knee MRI requested by the Traumatology and Orthopaedics Service between May 2007 and June 2011. As criteria for inclusion, men and women with skeletal maturity and absence of significant findings in the MRI study or in the CL or in the menisci were admitted. 147 MRI from people with active physis and presence of lesions in the CL or in the menisci in MRI were excluded. Image technique Sagittal and coronal slices of 3-4 mm in thickness were made using a superconductive 1.5 Tesla (Siemens) magnet, a coil of quadrature surface as transmitter and receptor, and with the patient in supine position, the knee extended and in external rotation. A magnetic field was generated from which a cubic space of 170 mm side that contains the knee was selected. Sagittal slices were used to obtain the measurements subject of this study. The radiologist selected the sagittal image that shows the insertion points of the ACL and PCL in the femur and in the tibia more clearly. Each sagittal slice is in a precise position –represented by the abbreviation (pos)– which is measured in mm, and represents the distance from this slice to the centre of the magnetic field (Fig. 2).

Data processing

We recorded the following parameters using the Dicom Works software and processed by the program Cruliant-ETSIB ® (EHU-Superior Engineering School) to show the dimensions of each bar in full scale (Fig. 3). The radiologist and the main author of this article assessed twice the validity of the parameters. Absolute variables determine the real

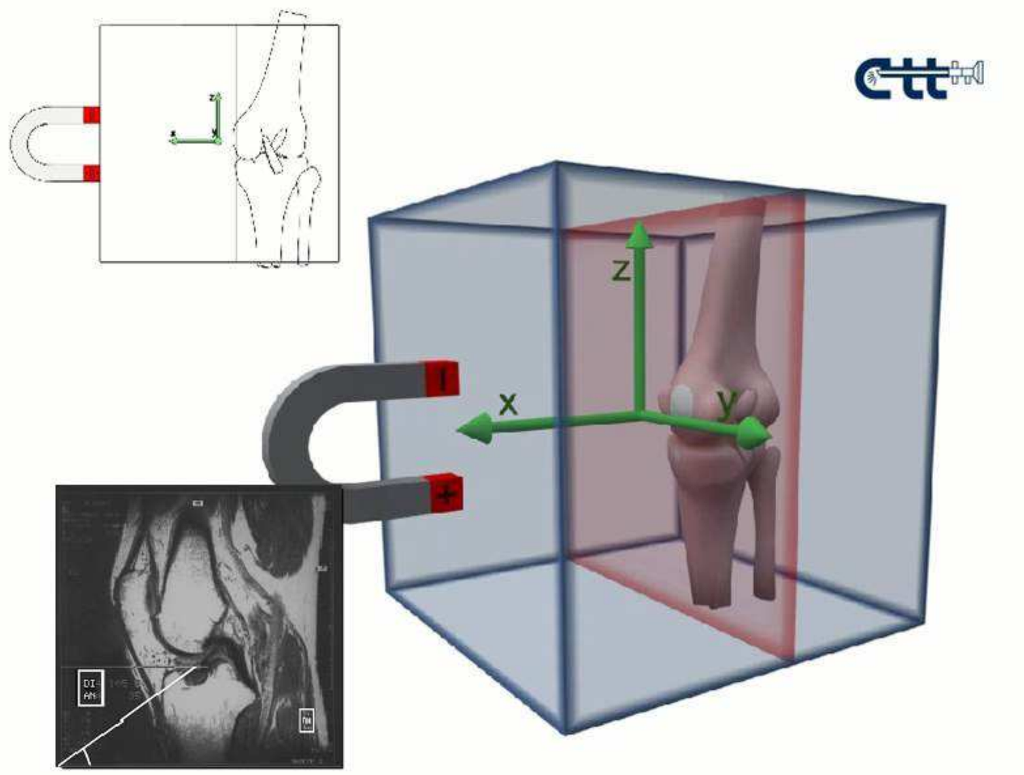

Fig. 2. Three-dimensional coordinate axis created from the selected sagittal MRI image. Cubic initial space generated from the magnetic field from which the final sagittal MRI image is selected.

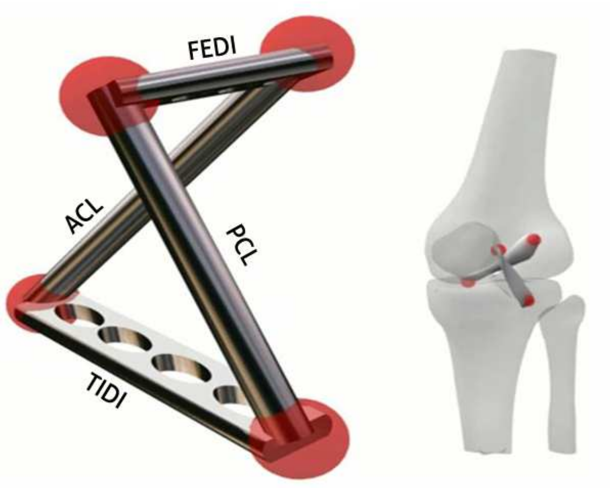

Fig. 3. Three-dimension recreation of the 4-bar linkage device reproduced from the CRULIANT-ETSIB® data. Location of this device inside a theoretical knee.

spatial distance between the central insertion points of the CL in the knee, while relative variables are scaled measurements that reflect their value independently from the size of the knee.

Femoral insertion parameters: FEDI (length of the bar linkage system of the femur), FEDI/PCL (scaled value of FEDI)

Tibial insertion parameters: TIDI (length of the bar linkage system of the tibia), TIDI/PCL (scaled value of TIDI)

Functional Unit Variables: ACL (length of the vector that represents the ACL in the space), PCL (length of the vector that represents PCL in the space), PCL/ACL (ratio between ACL and PCL), TIDI/FEDI (quotient between the bar linkage systems of the tibia and the femur).

Statistical analyses

A descriptive transversal and observational study was designed. The quantitative parameters were organised in two subgroups: absolute variables (FEDI, TIDI, ACL, PCL) and relative variables (FEDI/PCL, TIDI/PCL, PCL/ACL, TIDI/FEDI). A comparative study was also conducted by sex (men and women) and per side (right and left knees). Due to an unexpected result, it was necessary to divide the population into 4 subgroups, taking into account sex and laterality.

The descriptive analysis of the categorical variables (age, sex and laterality) will include frequency and percentage values for every parameter. Statistical analysis has been carried out using Pearson's Chi2 test. Kolmogorov-Smirnov test was used to prove the normality of the variables, and t-Student test to test the suitability of the parametric test when comparing median values (except in those who did not fulfill the requirements of normality which were obtained by means of the Wilcoxon non-parametric test). For the quantitative variables, mean, median, standard deviation, confidence interval and percentiles will be presented. Data have been processed and analysed by using Microsoft Office-Excel and analysed using SAS v9.2, IBM SPSS v.22 and Stata v.11.2 statistical programs.

Ethical considerations

The manuscript submitted does not contain information concerning medical device(s) or drug(s). No funds were received in support of this work.

RESULTS

This study included 200 MRI (92 men and 108 women), with a mean of 41 years of age (17- 84), and 109 right knees (54.5%) and 91 left knees (45.5%) were examined. No significant differences ($p \geq 0.05$) existed as regards the distribution by age according to sex or the side studied. Absolute and relative variables will be described in the text and dispersion measures will be added to their corresponding images.

Absolute variables. The distance between the central insertion points of both CL in the femur (FEDI) is 19.23 mm on average, being rare values inferior to 15 mm (10th percentile). The distance between the central insertion points of the CL in the tibia (TIDI) is 27.78 mm on average, with values above 32.63 mm being infrequent (90th percentile). The vector that represents the distance between the femoral and tibial insertions of the CL is, on average, 31.66 mm in ACL and 31.99 mm in PCL (Fig. 4).

Relative variables. The scaled measurements of FEDI and TIDI absolute variables reflect their value independently of the size of the knee. They are expressed as the quotient FEDI/PCL on the femoral side, with a mean of 0.62 (95% confidence interval: 0.60-0.64). We found no significant differences comparing sexes (0.62 in men and women), which balances the differences observed in its absolute value when analysed proportionally to the size of the knee. We found no significant differences comparing both sides (right 0.61; left 0.63). The quotient TIDI/PCL reflects the tibial relationship, with a mean value of 0.87 (95% confidence interval: 0.86-0.88). We found no significant differences in the comparison between men (0.87) and women (0.86), or between the right sides (0.87) and left sides (0.87). The TIDI value, different by sex and side in its absolute value, is balanced analysing it proportionally to the size of the knee. The relationship between the lengths of both CL is expressed by the quotient PCL/ACL, whose mean value is 1.02 (95% confidence interval: 0.99-1.05). This relationship remains constant without significant differences in the division of our sample by sex (men: 0.99/ women: 1.05) or by side (right: 1.03/ left: 1.00). The quotient TIDI/FEDI represents a magnitude of the objective relation between the insertions of both CL in the femur and in the tibia, A)

Variables	Mean	Median	SD	CI 95%	Percentiles 10	25	75	90
FEDI	19,23	19,00	2,83	18,84 – 19,63	15,63	17,33	20,91	22,81
TIDI	27,78	27,42	3,52	27,29 – 28,27	23,51	25,37	30,15	32,63
ACL	31,66	31,49	4,53	31,03 – 32,29	25,56	28,53	34,76	37,44
PCL	31,90	31,56	4,73	31,24 - 32,56	26,23	28,89	35,21	38,31

B)

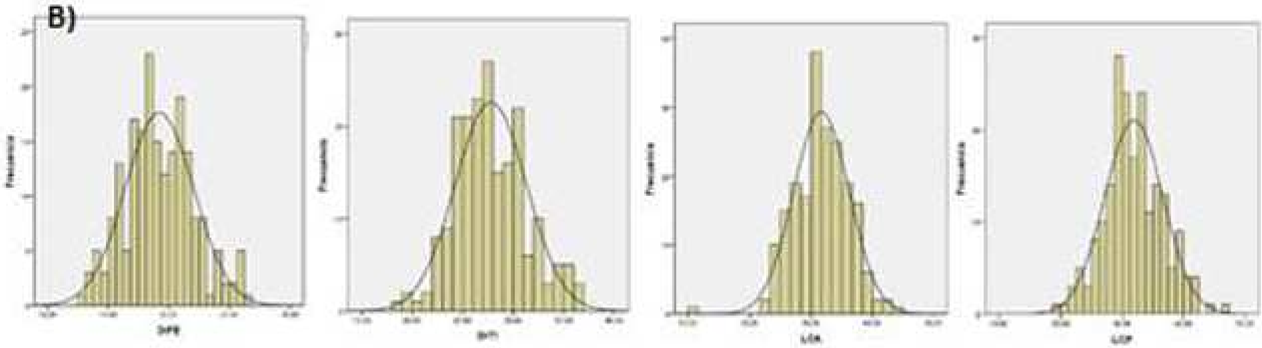

Fig. 4. (A) Absolute variables. SD (standard deviation) CI (confidence interval). **(B)** Histograms of absolute variables.

A)

Variables	Mean	Median	SD	CI 95%	Percentiles 10	25	75	90
FEDI/PCL	0,62	0,62	0,13	0,60 – 0,64	0,50	0,54	0,67	0,73
TIDI/PCL	0,87	0,87	0,08	0,86 – 0,88	0,78	0,82	0,92	0,98
PCL/ACL	1,02	0,99	0,23	0,99 – 1,05	0,82	0,90	1,10	1,22
TIDI/FEDI	1,45	1,42	0,18	1,43 – 1,48	1,23	1,33	1,58	1,69

B)

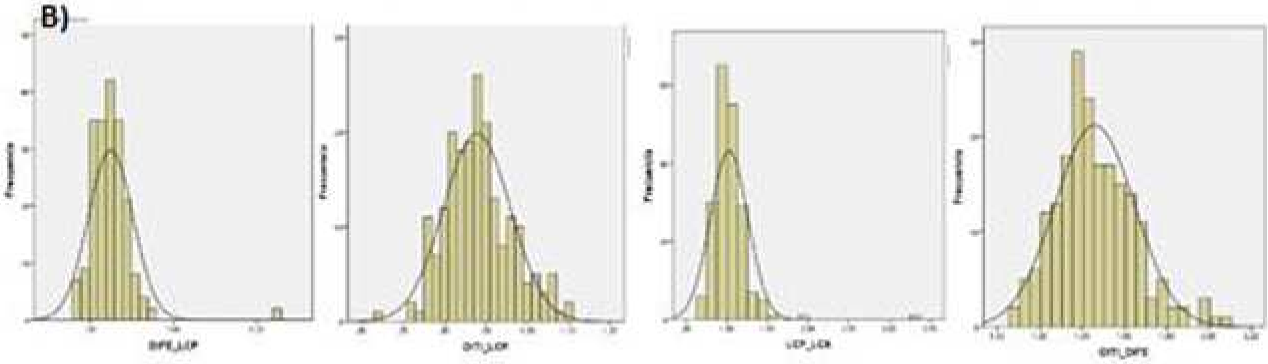

Fig. 5. (A) Relative variables. SD (standard deviation) CI (confidence interval). **(B)** Histograms of relative variables.

A)

	FEDI		
	MEN	WOMEN	P value
RIGHT	20,55 (2,71)	17,85 (2,38)	< 0,0001
LEFT	20,64 (2,91)	18,34 (2,21)	< 0,0001
P value	0,884	0,280	

	TIDI		
	MEN	WOMEN	P value
RIGHT	30,40 (3,4)	26,40 (2,76)	< 0,0001
LEFT	28,39 (3,61)	26,22 (2,64)	< 0,0001
P value	0,008	0,73	

B)

TIDI/FEDI	MEN	WOMEN	P value
RIGHT	1,49 (0,17)	1,49 (0,20)	0,877
LEFT	1,38 (0,17)	1,44 (0,18)	0,172
P value	0,005	0,145	

Fig. 6. (A) FEDI and TIDI variables: comparison by sex and side. **(B)** TIDI/FEDI variable: comparison by sex and side.

and its mean value in the studied population is 1.45 (95% confidence interval: 1.43-1.48) (Fig. 5). We found no statistically significant differences between the subgroup of men (1.44) and women (1.47). However, when comparing sides, the value obtained in right knees (1.49) is statistically higher than the one obtained in left knees (1.41).

Comparative study by sex. We observed statistically significant differences ($p < 0.05$) in all absolute variables, with the results being greater in men than women. Nonetheless, the results comparing relative variables did not show statistically significant differences ($p > 0.05$).

Comparative study by side. No statistically significant differences were observed regarding absolute variables, except in FEDI. In this case, the results on the right were greater than on the left side. We found no significant differences in the comparison of relative variables.

Comparative result of unexpected results. In order to find an explanation for the differences found in FEDI according to the side studied, an in-depth analysis was conducted. TIDI and TIDI/FEDI showed statistically significant differences between right and left knees in men, with the right one being greater. This behaviour was not observed in women, not showing their knees significant differences per side (Fig. 6).

DISCUSSION

The FEDI distance was previously calculated by Bradley and O'Connor, who realized their measurements on cadaveric knees in a bidimensional view based on radiological images, and their results were 14.5 mm and 12.8 mm respectively. Based on MRI images, Mediavilla published a FEDI distance of 18.7 mm in a two-dimensional plane, and 20.35 m in its tridimensional study. The insertion centres of ACL and PCL in the femur are in different sagittal planes. Consequently, the vector representing the distance between both points has an oblique path and it is quantitatively greater than that obtained in a bidimensional sagittal plane. This fact explains the differences found between the values in the two-dimensional plane and those of the tridimensional studies (19.23 mm in this study) (Fig.7).

In the reconstructive surgery of the ACL, it is widely accepted that one of the key moments is the decision of its femoral insertion point. Variations at this level, which applied to the current tridimensional approach, would signify modifications in the magnitude of FEDI, are well known. A small FEDI is obtained when the ACL insertion is displaced anteriorly through the roof of the intercondylar space or on the medial face of the lateral condyle of the femur: this is considered the most frequent mistake during surgery, with a mean of 52.5% of failure of the graft in tunnels placed this way. A high FEDI value reflects an excessively posterior insertion point of the ACL with respect to the PCL, which reproduces a plasty that undergoes an excessive tension with the extension of the knee, and a slight loosening with flexion.

The distance between tibial insertions (TIDI) has been calculated either in anatomical or radiological studies (Fig. 8). Although the reference points taken in ACL and in PCL vary, the mean value published is 30.5 mm. Unlike what happens in the fe-

Fig. 7. FEDI vector in sagittal MRI view.

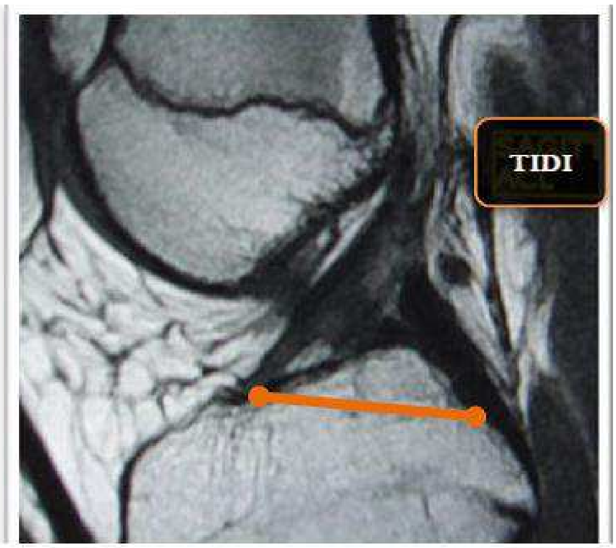

Fig. 8. TIDI vector in sagittal MRI view.

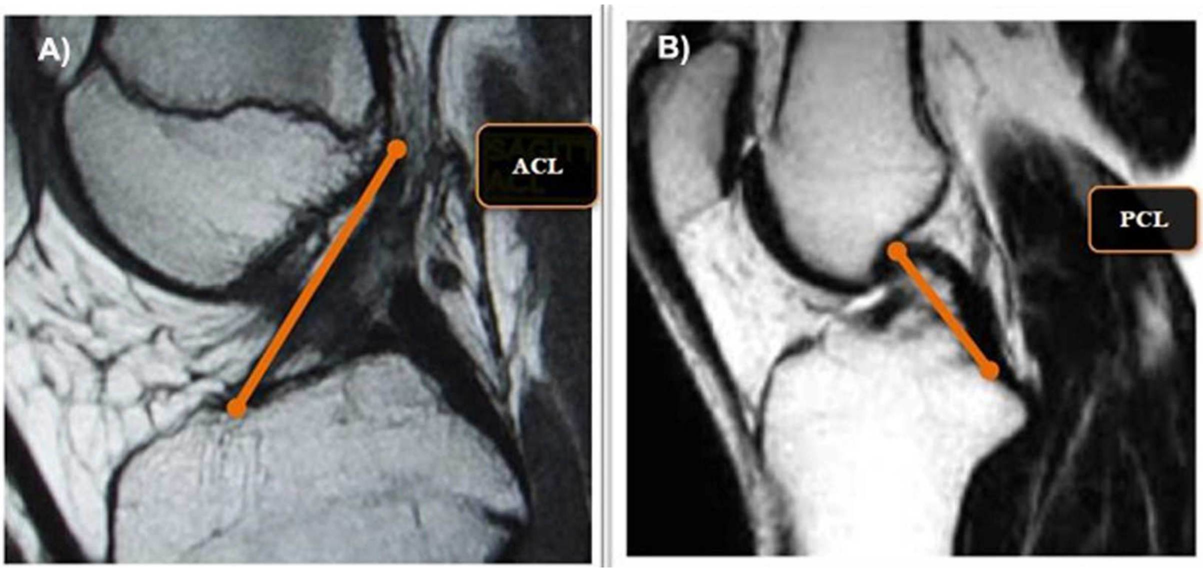

Fig. 9. (A) ACL vector in sagittal MRI view. **(B)** PCL vector in sagittal MRI view.

mur, the insertion of both CL is situated in the same sagittal plane, and therefore, the obtained vector represents the real distance between the two central insertion points.

Regarding the ACL reconstructive surgery, variations in the tibial insertion point have less influence on the final behaviour of the ligament than in the case of the femoral insertion. A lower TIDI value means an excessive posteriorisation of the tibial insertion of ACL, reproducing a ligament that potentially would undergo an impingement with the PCL and would be excessively stretched with the extension of the knee. A higher TIDI value would reproduce a graft that could undergo impingement with the roof of the intercondylar space with the knee extended. With the knee flexed, the ligament would experience excessive tension that could promote its re-breakage.

The ACL value expresses the distance between the mid-point of the femoral and tibial insertion of the ligament. MRI examination was done with the knee extended, the position in which the ACL is tensed, so the mean value represents the real length of its central axis. The present results are comparable to those published by Bradley (32 mm), O'Connor (29.9 mm) and Mediavilla (31.70 mm), as well as in different anatomical studies published in the literature (in which the mean length of 32 mm is accepted).

The PCL vector expresses the real distance of a straight line between the mid-points of its femoral and tibial insertion (Fig. 9). It represents vectorially the PCL, which folds itself near its femoral insertion when the knee is extended. This is an adaptation of the ligament to the external rotation of the tibia that occurs in the last degrees of extension. The differences between the measures published in the literature (Bradley 28.5 mm, O'Connor 32.2 mm, Mediavilla 36 mm, anatomical studies 32-38 mm) and the current one could be due to the election of the central insertion points of the ligament. The PCL insertion is wide and often not well defined in studies based on simple X-rays. Anatomical studies made in the 2-dimensional plane show the lowest values whereas direct measurements of the ligament in its entire length show the upper ones.

The relative values (FEDI/PCL, TIDI/PCL, PCL/ACL, TIDI/FEDI) reflect the value of the scaled bar links, so that they are independent of the size of the knee. In all cases, there is a minimal dispersion of their results, being a constant representative of the four-bar device analysed.

The PCL/ACL variable links both lengths without representing a spatial anatomical reference between them. Although this parameter does not appear in the bibliographical references included, its value was calculated from the dimensions of the analysed CL. With the values published by Girgis the PCL/ACL quotient is 0.99 (38.1/38.2). According to the radiological studies by Bradley, its value is 0.89 (28.5/32), while O'Connor obtained results somewhat higher: 1.07 (32.2/29.9). In his study with MRI images, Mediavilla published a PCL/ACL quotient of 1.13 (36/31.70). Regardless of the technique used, it seems to be a trend to balance in ACL and PCL's length.

The normality of this value in the ligamentoplasty would not represent the normality of the reconstructed composition, since there are errors that can occur and simultaneously be compensated during the surgery. It encourages us to make harmonic reconstructions taking into account the size of the affected knee (being greater as the size of the knee increases). It is not only about reconstructing the damaged ACL, but also of doing it in relation to the native PCL and in harmony with it.

The TIDI/FEDI quotient represents an objective magnitude of the relationship between both insertions of the CL. Its balanced behaviour is the subject of this study, and constitutes a constant whose mean value is 0.45 (0.01). We can consider this value as a constant representative of the four-bar linkage device analysed. The TIDI/FEDI concept reliably expresses the most frequent mistakes in the surgical technique, which is the existence of a femoral or tibial tunnel in an excessively anterior position. Both the increase in the TIDI value and the decrease in the FEDI value are mathematically expressed in the same direction of the quotient. In both cases these errors are reflected in an increase in its value. It represents, objectively, the detrimental effects that these placements would have for a potential graft.

When analysing the results by gender, either the FEDI, TIDI, ACL and PCL values were greater in males than in females, with the differences being statistically significant. According to the anthropometric data published, either in height, weight or dimensions of the knees of men are, on average, greater than those of women. We can deduce that the larger the size of the knee is, the greater will be, proportionally, the measured distances.

In both sides, we found no significant differences in FEDI, ACL and PCL measurements, suggesting that their value is independent of the studied side. Nevertheless, we found differences in the TIDI value, being the right side (28.27 mm) significantly greater than the left one (27.20 mm). A detailed analysis of the data revealed that, in the subgroup of men, the TIDI/FEDI value of right knees was greater than the left one (1.49 vs 1.38). In this same subgroup, the FEDI value does not show differences regarding the analysed side. However, TIDI value is greater in right knees than in left (30.40 vs 28.39). It can be deduced that there is an anatomical difference between the right and left tibias of the included population, involving an increase in the distance between the centres of the insertions of the CL. However, regarding the anthropological articles reviewed, it seems to be an asymmetry in the lower limbs that would go in favour of the non-dominant side, the left. With the available data we cannot explain whether the difference observed in our population is due to a greater development of the right leg, to a typical characteristic of the studied sample, or whether it defines the general population. The reasons why this difference exists and is present only in males surpass the objectives of this study. In the gathering of data, no information was obtained about the dominant side of the individuals in their lower limbs, which might have generated an uncontrolled selection bias.

One of the potential limitations of this study is the existence of a possible selection bias. The population sample used is taken from a hospital and not randomly (patients that for some reason go to the hospital with knee problems to which an MRI is performed that turns out normal). By not having been selected through purely random procedures, it could have some characteristics that make it different from the general population. Uncontrolled variables may also exist (occupation, sports activity, traumatic background) that could influence the values of the studied parameters. Another limitation of this study is the potential bias of information incurred by the observer (in the measurement of the MRI or in the processing of the data). In accordance with the revised bibliography, we consider that not including the weight and size of the participants as a correlation and association variable is not a limitation of our study.

Conclusions

The anatomic pattern between the CL in the knee reproduces a four-bar linkage model that is represented by the anthropometrically constant TIDI/FEDI value and can be reproduced in clinical practice. The value of this variable in the healthy population is 1.45. This relationship allows the orthopaedist to reconstruct an anatometric ligament that respects this interrelation and that constitutes the central pivot of the knee, essential for its normal working.

This value could be the basis for developing, presurgically, an individualised four-bar device for each patient that imitates the anatomic pattern existing in the general population. The proposed model would, therefore, provide the surgeon with an effective tool to increase accuracy in the most delicate moment of the surgery: the placement of the femoral and tibial tunnels. To date, different navigation systems have been used to help the surgeon recreate intrasurgically a volumetric model of a CL, but they do not measure nor relate it. The results provided by our investigation could be considered a new frame of reference for the surgical navigation systems.

As a corollary of our results, and opening a new path for future research, the anatomical model represented by the physiological TIDI/FEDI quotient could be used as a complementary tool to objectively assess the results of the ligamentoplasties due to its constant value, suggesting the need of further investigation in this field.

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