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Femoral tunnel placement accuracy analysis in ACL reconstruction: a retrospective study

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Femoral tunnel placement accuracy analysis in ACL reconstruction: a retrospective study

Application dissertation for the Master's degree in Medicine,
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Declaration of Scientific Integrity

I, Bárbara Rolla Palhares Vieira, enrolled in the Integrated Master's Program in Medicine at School of Medicine and Biomedical Sciences of the University of Porto, hereby declare that, in accordance with the provisions of paragraph a) of article 14 of the Code of Ethical Conduct of the University of Porto, the content of this dissertation reflects perspectives, research work, and my interpretations at the time of its submission. By submitting this dissertation, I also declare that it contains the results of my research work and contributions that have not been previously submitted to this or any other institution. Furthermore, I declare that all references to other authors are in compliance with attribution rules and are cited in the text and identified in the references section. The project does not include any content whose reproduction is protected by copyright laws. I am aware that the practice of plagiarism constitutes a form of academic misconduct.

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The advance of Medicine depends on the progress of Science.
And "the important thing in Science is not so much to obtain new facts as to discover new ways of thinking about them" - William Lawrence Bragg.

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Resumo

Contexto: A rotura do ligamento cruzado anterior (LCA) constitui a lesão ligamentar mais comum no joelho, sendo o tratamento cirúrgico o mais utilizado. O objetivo último da cirurgia é restaurar a anatomia e biomecânica nativas e, para isso, a localização do ponto de inserção do túnel femoral revela-se crucial.

Objetivos: Neste estudo, objetivámos avaliar a acuidade cirúrgica do posicionamento do túnel femoral na cirurgia de reconstrução do LCA. Adicionalmente, analisámos se o posicionamento do túnel femoral tem implicações clínicas recorrendo ao questionário *Knee injury and Osteoarthritis Outcome Score* (KOOS) e determinámos a influência de parâmetros antropométricos e de fatores relacionados com a cirurgia no posicionamento do túnel femoral.

Métodos: Foi realizado um estudo de coorte retrospetivo, com dados colhidos de um total de 77 doentes submetidos a cirurgia de reconstrução do LCA entre 2010 e 2023 na Unidade Local de Saúde de Santo António (ULSSA). Só foram incluídos doentes que tivessem realizado ressonância magnética (RM) pós-operatória. Foi feita uma análise imagiológica das RMs através do programa *3D Slicer* e aplicando o método dos quadrantes de Bernard, segundo o qual a distância t representa a linha de Blumensaat e a distância h corresponde à altura da fossa intercondilar. Foi também realizada uma análise clínica pós-operatória dos doentes recorrendo aos questionários KOOS, que apenas estavam disponíveis em 41 dos 77 doentes. Adicionalmente, foram recolhidos dados antropométricos e dados relacionados com a cirurgia.

Resultados: Esta amostra apresentou uma média de idades no momento da cirurgia de 28 anos, sendo 78.4% homens. O enxerto mais usado como neoligamento foi o tendão dos isquiotibiais. O ponto médio de inserção do túnel femoral localizou-se a 37.59% ± 5.70% da distância t – variando entre 26.17% e 53.70% – e a 23.55% ± 5.14% da distância h – variando entre 12.97% e 37.19%. Isto significa que o ponto médio obtido no estudo se localizou numa posição mais superficial e alta, comparativamente àquela considerada anatómica por Bernard e Hertel (a 24.8% da distância t e a 28.5% da distância h). Relativamente à estratégia de localização do túnel femoral, 73.0% dos doentes foram operados segundo a técnica *freehand*, enquanto os *offset aimers* foram utilizados em 27.0% dos casos. Os *offset aimers* permitiram uma inserção mais profunda ao longo da linha de Blumensaat, com significância estatística (34.24% ± 5.00% vs. 38.84% ± 5.47%, $p = 0{,}0016$). O coeficiente de variação obtido ao utilizar *offset aimers* foi de 14.60% para t(%) e de 21.91% para h(%), enquanto que através da técnica *freehand* foi de 14.08% para t(%) e de 21.40% para h(%). De acordo com o consenso da Sociedade Europeia de Traumatologia Desportiva, Cirurgia do Joelho e Artroscopia, um túnel femoral bem posicionado foi obtido em 71.6% dos casos, no entanto, não foi encontrada uma associação entre os pontos considerados mal posicionados (28.4% dos casos) e piores resultados clínicos no KOOS. Embora nenhuma relação estatisticamente significativa tenha sido relatada entre o posicionamento do túnel femoral e o KOOS neste estudo, um padrão de tendência foi observado: quanto mais posterior o túnel foi posicionado, melhores foram os resultados clínicos obtidos em todas as subescalas do KOOS. Quando apenas se consideraram as reconstruções realizadas com a técnica *freehand*, esta relação foi mais forte com uma subescala particular do KOOS, com um $p = 0.052$ para t(%) e um $p = 0.062$ para h(%).

Conclusão: Deve haver um esforço por parte dos cirurgiões ortopedistas em localizar o ponto de inserção do túnel femoral mais posteriormente, isto é, num local mais profundo (ao longo da linha de Blumensaat) e mais baixo (ao longo da altura da fossa intercondilar), já que existe um padrão de tendência no sentido de melhores resultados clínicos com este posicionamento. Neste estudo, usando *offset aimers*, um local de inserção mais profundo foi possível e, através da técnica *freehand*, um posicionamento mais superficial foi obtido, contrariamente à hipótese teórica de que não considerando a individualidade de cada doente, os *offset aimer devices* são mais propensos a levar a posicionamentos não anatómicos.

Palavras-chave

Ligamento cruzado anterior, posicionamento do túnel femoral, acuidade cirúrgica, método dos quadrantes de Bernard.

Abstract

Background: The rupture of the anterior cruciate ligament (ACL) is the most common ligament injury of the knee, being the surgical treatment the most employed. The ultimate goal of the surgery is to restore the native anatomy and biomechanics of an uninjured ACL, and for this, the location of the femoral tunnel insertion point reveals itself crucial.

Objectives: In this study, we aimed to evaluate the surgical accuracy of femoral tunnel placement in ACL reconstruction. In addition, we assessed whether or not there are clinical implications of femoral tunnel placement using the Knee injury and Osteoarthritis Outcome Score (KOOS) and determined the influence of anthropometric parameters and surgery-related factors on femoral tunnel placement.

Methods: A retrospective cohort study was conducted with data collected from a total of 77 patients who underwent ACL reconstruction surgery between 2010 and 2023 at Unidade Local de Saúde de Santo António (ULSSA). Only patients who had undergone postoperative magnetic resonance imaging (MRI) were included. An imaging analysis of the MRIs was performed using the 3D Slicer program and applying Bernard's quadrant method, according to which distance t represents Blumensaat’s line and distance h corresponds to the height of the intercondylar notch. A postoperative clinical analysis of the patients was also conducted using KOOS, which were only available for 41 of the 77 patients. Additionally, anthropometric data and surgery-related data were collected.

Results: This sample had an average age of 28 years at the time of surgery, with 78.4% being men. The most commonly used graft for the neoligament was the hamstring tendon (83.8%). The mean femoral tunnel attachment site was located at 37.59% ± 5.70% of distance t – varying between 26.17% and 53.70% – and at 23.55% ± 5.14% of distance h – varying between 12.97% and 37.19%. This means that the mean point obtained in the study was located in a shallower and higher position compared to that considered anatomical by Bernard and Hertel (at 24.8% of distance t and at 28.5% of distance h). Regarding the tunnel localization stratey, 73.0% of the patients were operated using the freehand method, while the offset aimers were used in 27.0% of the cases. Using offset aimers allowed for a statistically significant deeper insertion site location along Blumensaat’s line (34.24% ± 5.00% vs. 38.84% ± 5.47%, p-value = 0.0016). The coefficient of variation obtained when using offset aimers was 14.60% for t(%) and 21.91% for h(%), whilst through freehand technique was 14.08% for t(%) and 21.40% for h(%). According to the European Society of Sports Traumatology, Knee Surgery & Arthroscopy consensus, a well-positioned femoral tunnel was achieved in 71.6% of cases, however no association was found between the considered misplaced points (28.4% of cases) and worse clinical outcomes in KOOS. Despite no statistically significant relationship was reported between femoral tunnel placement and KOOS in this study, a trend pattern was observed: the more posterior the tunnel was positioned, the better were the clinical results in all KOOS subscales. When only considering reconstructions performed with a freehand technique, this relation was stronger with one particular KOOS subescale, with a p-value of 0.052 for t(%) and 0.062 for h(%).

Conclusion: Orthopedic surgeons should make an effort to place the femoral tunnel insertion point more posteriorly, that is, in a deeper position (along Blumensaat's line) and lower (along the intercondylar notch height), as there is a trend pattern indicating better clinical outcomes through this placement. In this study, using offset aimers allowed a deeper (i.e., more posterior) tunnel insertion attachment, whilst through a freehand technique shallower (i.e., more anterior) insertion sites were obtained, contrary to the theoretical hypothesis that by not considering the individuality of each patient, offset aimer devices were more likely to lead to non-anatomical placements.

Keywords

Anterior cruciate ligament, femoral tunnel placement, surgical accuracy, Bernard quadrant method.

Acronyms

ACL, Anterior Cruciate Ligament

ADL, Activities of Daily Living

AMP, Anteromedial Portal

BMI, Body Mass Index

CT, Computed Tomography

ESSKA, European Society of Sports Traumatology, Knee Surgery & Arthroscopy

IKDC-SKF, International Knee Documentation Committee - Subjective Knee Form

KOOS, Knee injury and Osteoarthritis Outcome Score

MRI, Magnetic Resonance Imaging

OI, Outside-in

PASS, Patient Acceptable Symptom State

PROMs, Patient-Reported Outcome Measurements

QOL, Quality Of Life

ROI, Region Of Interest

TT, Transtibial

WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index

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Introduction

The knee has been regarded as the most complex joint in the human body, with the cruciate ligaments being considered the fulcrum of its kinematics. Anterior cruciate ligament (ACL) is a very important stabilizing ligament of the knee as it controls anterior translation of the tibia, as well as resists tibial rotation and helps provide varus-valgus stability when the knee is in full extension[1]. It originates at the posteromedial aspect of the lateral femoral condyle, courses distally in an anterior and medial direction, ultimately attaching to the anteromedial aspect of the tibia between the condyles.[2]

In addition to its significance in the normal functioning of the knee, the ACL stands as the most commonly injured knee ligament - accounting for about 50% of knee injuries -, especially in ahthletes[3]. Sports involving rotational movements such as soccer, american football, basketball or tennis are the ones responsible for the largest number of ACL injuries, but virtually any sport that involves explosive running, jumping, or sudden changing of direction places the athlete at risk for ACL injury. It can occur due to low-energy non-contact injuries (70% of ACL ruptures) sustained during a previously mentioned athletic activity, when an athlete running or jumping abruptly decelerates and changes direction, or falls in a manner that results in a valgus stress, abduction and minimal knee flexion, coupled with internal rotation and anterior translation of the tibia on the femur, as well as femoral adduction and ankle eversion.[4] And also due to low-energy contact injuries (e.g., direct blow to the lateral aspect of the knee, causing hyperextension and/or valgus deformation of the knee, commonly seen in american football)[5] or even following high-energy injuries (e.g., motor vehicle collisions and downhill skiing).[3] In the USA, there are estimated to be about 200.000 ACL ruptures each year (translating to an annual incidence in the general population of roughly 1 in 3.500), of which 120.000 undergo ACL reconstructions.[6,7]

Surgical reconstruction is generally the treatment of choice with the objective of restore joint stability, allowing a safe return to sport/activities of daily living (ADLs) without limitations and, most importantly, avoiding early degenerative changes. Surgery involves replacing the ACL with a neoligament, which entails creating a tunnel through the femur and another through the tibia, allowing the passage and fixation of the graft. The ultimate goal is to reproduce the individual anatomy of the patient's ACL, restoring its native dimensions, position, orientation, tensioning patterns and insertion site, in order to resemble the kinematics of an uninjured knee.[8–10] This approach is called "anatomic ACL reconstruction" and is considered the current *gold standard* of surgical ACL reconstruction.

While achieving proper placement of the tibial tunnel is relatively straightforward, positioning the femoral tunnel can be more challenging. Regarding this topic, two variables take account, the drilling technique and the tunnel localization strategy. Femoral tunnel placement can be accomplished using either a method reliant on the tibial tunnel (transtibial technique) or an approach independent of the tibial tunnel (anteromedial portal and outside-in techniques). Historically, there was a shift from a TT approach to a AMP/OI approach[11–13], since AMP and OI techniques enable reaming the femoral tunnel unconstrainedly with free angles at a right position[14,15], therefore avoiding an anterior malplacement and providing a better restoration of the anatomical femoral footprint.[16–19] At our institution, all surgeons opt for the AMP technique.

Moreover, there are different tunnel localization strategies a surgeon can use, such as femoral offet aimer devices and freehand technique. Offset aimers are designed with fixed measurements to standardize the location of the tunnel, so they ensure consistent tunnel placement, which is beneficial especially for inexperienced surgeon, but has the disadvantage of not accounting for the anatomical variability among individual patients.[20,21] Among experienced surgeons, the freehand approach is tipically the preferred one, especially when remnants of the femoral attachment of the native ACL are visible. However, unlike acute cases, in cases of chronic ACL rupture, this footprint may not be apparent, so positioning may be estimated using a number of methods, including estimation from bony landmarks, such as the lateral intercondylar ridge or “resident’s ridge” and the lateral bifurcate ridge. The first one is situated on the posterior aspect of the lateral intercondylar notch wall, in the medial aspect of the lateral femoral condyle[22], delimitating the anterior border of the femoral tunnel insertion site; the second one runs perpendicular to the lateral intercondylar ridge, positioned between the conventionally defined “anteromedial” and “posterolateral” bundles insertion sites and delimitating the distal border of the femoral tunnel insertion site (surgeons aim to place the center of the tunnel in the center of the "anteromedial” bundle). However, since these bony landmarks emerge due to osseous adaptation in response to tensile forces from the ligament fibers, they gradually diminish in prominence in the absence of an intact ACL and might not be identified, so the surgeon can simply visualize the whole medial wall of the lateral femoral condyle and place the tunnel in the lower 30-35% of the intercondylar notch wall[23] or, as an alternative, rely on the “clock-face” method [24,25].

Although several clinical studies have established a statistically significant relationship between femoral tunnel positioning and patients’ clinical outcome[26–30], others have failed to do so.[31,32] Our hypothesis is that a femoral tunnel placed nearer to the anatomical ACL position yield more favorable clinical outcomes in comparison to non-anatomically placed tunnel positions.[33,34] As so, our primary objective is to evaluate the surgical accuracy of femoral tunnel placement in ACL reconstruction; and our secondary objectives are to assess whether or not there are clinical implications of femoral tunnel placement through Patient-Reported Outcome Measurements (PROMs) - particularly, KOOS (Knee injury and Osteoarthritis Outcome Score) - and to determine the influence of anthropometric parameters and surgery-related factors on femoral tunnel placement **(Figure 1)**.

Methods

The study was submitted for approval to the Ethics Committee and received a favorable opinion - approval reference 2023.233(196-DEFI/185-CE).

Participant Selection

The surgical records of ACL reconstruction procedures performed at our institution between 2010 and 2023 were analyzed, totaling 318 cases. Only patients who underwent postoperative Magnetic Resonance Imaging (MRI) following ACL reconstruction were included. Subsequently, 77 cases were selected for a three-dimensional reconstruction and radiological analysis. However, in 3 cases, this analysis was not feasible due to noise, resulting in a total sample of 74 patients. Of these 74, we were only able to collect the KOOS score from 41 patients' clinical records **(Figure 2)**.

Data Collection

Information regarding anthropometric parameters (such as age, gender, weight, height and BMI), surgery-related factors (such as primary attending surgeon, tunnel localization strategy, graft structure, femoral tunnel diameter and operated side), PROMs (particularly KOOS) and postoperative MRIs were collected from patients' clinical records and surgical reports.

Imagiological evaluation after ACL reconstruction

For imagiological evaluation, we applied quadrant method by Bernard *et al*. (1997)[33], according to which we can frame the point representing the center of the femoral tunnel on a grid bounded by distances t and h, using its partial coordinates (a,b). Distance t corresponds to the total sagittal diameter of the lateral femoral condyle measured along the roof of the intercondylar notch of the femur (also called Blumensaat's line); distance h corresponds to the maximum height of the intercondylar notch perpendicular to Blumensaat's line; distance a (which represents a partial length of distance t) measures the distance from the center of the femoral tunnel to the most dorsal subchondral contour of the lateral femoral condyle; and distance b (which represents a partial length of distance h) measures the distance from the center of the femoral tunnel to Blumensaat's line **(Figure 3)**. Distances a and b are expressed as percentages of t and h in order to standardize each patient's values, and several authors have estimated the anatomical location of the native insertion of the ACL on the femur.[33]

Originally, Bernard *et al.* reported that the center of the femoral insertion of ACL (in human cadaveric knees) was located at 24.8% of the distance t measured from the deepest subchondral contour [that is, (distance a/distance t)x100] and at 28.5% of the height h measured from Blumensaat's line [that is, (distance b/distance h)x100]. European Society of Sports Traumatology, Knee Surgery & Arthroscopy (ESSKA) formal consensus recommendations claim that a femoral tunnel may be deemed misplaced if its center falls outside the range of 19-29% of the proximal-distal dimension and 22-53% of the antero-posterior dimension, based on the quadrant method proposed by Bernard and Hertel.[35]

MRI images were exported from SECTRA® (Sectra AB, Linköping, Sweden) to 3D Slicer for three-dimensional reconstruction (through Volume Rendering tool) and image analysis (mainly through Markups and also Transforms tools). There was a need to perform 3D reconstructions to enable stable delineation of limits. An alternative would have been to overlay 2D images, however, this would compromise the precision of the study.

When selecting the "Display ROI" visualization, it was possible to navigate through sagittal slices of the volume and make cuts in our region of interest (ROI). For this purpose, three sagittal cuts were selected: a) one displaying the roof of the intercondylar notch of the femur (Blumensaat's line); b) one presenting the largest diameter of the lateral femoral condyle; and c) the first one showing the bone tunnel moving from medial to lateral **(Figure 4)**. These cuts allow the delineation of the necessary limits for the application of a plane: the upper limit corresponds to the total sagittal diameter of the lateral femoral condyle measured along the roof of the intercondylar notch of the femur (distance t), the lower limit is parallel to the upper border at the level of the posterior border of the lateral femoral condyle, the posterior limit corresponds to the maximum height of the intercondylar notch perpendicular to the upper limit (distance h), and the anterior limit is parallel to the posterior limit at the distal level of the lateral condyle.

Then the center of the tunnel was determined by calculating the center of the circular area visualized in c), which corresponds to the first cut showing the bone tunnel, moving from medial to lateral from the intercondylar notch of the femur. Subsequently, in the "Transforms" section, a grid was created on the previously delimited plane, in order to frame the center of the femoral tunnel according to Bernard's method. The center of femoral tunnel was designated as point K, from which two more distances were measured: distance a, measuring the distance from point K to the most dorsal subchondral contour of the lateral femoral condyle, and distance b, measuring the distance from point K to Blumensaat's line. The four distances (t, h, a and b) are expressed in **Figure 5**.

In order to clarify high/low, deep/shallow, anterior/posterior and distal/proximal anatomical terms at the level of the lateral condyle of the femur, which will be extensively used in this study to interpretate the results obtained, the scheme presented in **Figure 6** was created.

Clinical outcome evaluation after ACL reconstruction

Clinical outcomes after ACL reconstruction were evaluated using PROMs, an essential tool to comprehend the patients' perspective on the impact of ACL injury and its treatment.

Although currently there is no universally recognized *gold standard* PROM, the two most widely utilized following ACL injury are IKDC-SKF and KOOS (which derived from WOMAC). In our institution the questionnaire used is KOOS, therefore it was from this that clinical outcome data was collected for the current study. KOOS is directed to young and middle-aged people with posttraumatic OA or injuries that may lead it (e.g., ACL, meniscal, or chondral injury) and assesses the patient's perception of knee-related symptoms and function over the previous week, by making 42 questions across 5 domains: (1) pain, (2) other symptoms (such as knee stiffness, swelling, grinding, clicking, catching and range of motion restriction), (3) difficulty experienced during ADLs, (4) difficulty experienced during sport/recreational activities and (5) knee-related QOL **(Figure 7)**. It takes 10 minutes to complete the questionnaire. Each item is scored on a 5-point Likert scale (0-4), and the 5 dimensions are scored separately as the sum of all corresponding items and then transformed into a 0-100 scale (where 0 corresponds to extreme problems and 100 to no problems). A total score of the 5 domains has not been validated and is not recommended.[36] KOOS is a valid, reliable and responsive self-administered instrument that can be used for short-term (1-2 years), midterm (3-15 years) and long-term (>15 years) follow-up of several types of knee injury including ACL.

Additionally, we applied Patient Acceptable Symptom State (PASS) into KOOS[37]. PASS evaluates whether the patient is satisfied with the outcome of treatment, by asking the following question to patients who had undergone ACL reconstruction: “Taking account of all the activity you have during your daily life, your level of pain, and also your activity limitations and participation restrictions, do you consider the current state of your knee satisfactory?”. Threshold values for PASS in KOOS were established by Muller *et al*.[38] and are the following: Pain, ≥88.9; Knee-related Symptoms, ≥57.1; ADL, =100; Sport and Recreation, ≥75.0; and Quality of Life (QOL), ≥62.5.

Statistical Analysis

Continuous data are expressed as mean ± standard deviation (SD), while categorical data are expressed as number of cases and respective percentage.

The Shapiro-Wilk test was used to assess the normality of the groups. A comparison of two independent groups was performed using either an unpaired t-test or a Mann-Whitney U test, depending on the normality. Comparisons among three or more independent groups were conducted using either a One-Way ANOVA or a Kruskal-Wallis test, depending on the normality. Correlation between continuous variables were performed using either the Pearson or the Spearman test, based on the data normality. To assess relative risk increase, linear or binary logistic regression was performed, depending on whether the variables were continuous or categorical, respectively. A p-value < 0.05 was considered statistically significant. Statistical analysis was carried out using GraphPad (Prism; Version 10.2.0) and SPSS (IBM; Version 29.0) for Windows.

Results

Sample description

Of the 77 patients selected, 78.4% were males, 21.6% were females, and the mean age at the time of surgery was 28.09 ± 10.31 years old (ranging from 13 to 51). Almost half of the patients underwent surgery on each side. Among graft structures, 83.8% used hamstrings, 9.5% quadriceps, 5.4% patellar and 1.4% allograft. Regarding the tunnel localization strategy, two primary attending surgeons (who performed 73% of the reconstructions) resorted to the freehand approach, whilst the remaining surgeons (who performed 27% of the reconstructions) used an offset aimer. The follow-up time between surgery and KOOS assessment varied between 1 and 7 years. Detailed patients and surgery characteristics are depicted on **Tables I and II**, respectively.

Femoral tunnel placement

The distribution of the femoral tunnel insertion central points is presented in the following scatter plot **(Figure 8)**, with the calculated average point highlighted. The X axis corresponds to (distance a/distance t)x100 and the Y axis corresponds to (distance b/distance h)x100. The values of t(%) and h(%) varied between 26.2 and 53.7% for t(%) and 13.0 and 37.2% for h(%). The mean values obtained for t(%) and h(%) were respectively 37.6% ± 5.7% and 23.6% ± 5.14%.

As mentioned above, ESSKA formal consensus recommendations claim that a femoral tunnel may be deemed misplaced if its center falls outside the range of 19-29% of the proximal-distal dimension and 22-53% of the antero-posterior dimension,[35] based on the quadrant method proposed by Bernard and Hertel.[33] In order to understand which values were outside this recommended range (considered poorly positioned femoral tunnels), the following scatter plot was created **(Figure 9)**. In this study, 21 cases were outside the range considered well positioned, which represents 28.4% of the total.

Anthropometric and surgery-related factors

Regarding the determination of the influence of anthropometric parameters on femoral tunnel placement, no correlation was considered statistically significant and no trend pattern was observed **(Figure 10)**.

On the other hand, regarding the influence of surgery-related factors on femoral tunnel placement, no correlation was considered statistically significant, with the exception of the tunnel localization strategy chosen and specifically distance t **(Figure 11)**. In comparison to the freehand strategy, using offset aimers allowed for an inferior t(%) (34.24% ± 5.00% vs. 38.84% ± 5.47%, p-value = 0.0016) and an inferior, but not statistically significant, h(%) (21.91% ± 4.80% vs. 24.16% ± 5.17%, p-value = 0.0948). Additionally, the coefficient of variation obtained when using offset aimers was 14.60% for t(%) and 21.91% for h(%), very similar but slightly higher values than those obtained when opting for a freehand strategy, which were 14.08% for t(%) and 21.40% for h(%).

Clinical outcome evaluation after ACL reconstruction

Focusing now on the assessment of whether or not there are clinical implications of femoral tunnel placement through KOOS, an individual and independent analysis was carried out for each subscale of the score, since a total score of the 5 domains has not been validated and is not recommended.[36]

Through the graphs presented in **Figure 12**, we are able to better understand the relationship between the KOOS subscales and the femoral tunnel center location. The percentages of each KOOS subscale were divided into 7 clusters represented on a color scale, where red corresponds to the worst clinical outcome and green to the best.

No correlation between tunnel placement and KOOS subscales was considered statistically significant, which means that the values of t(%) and h(%) did not lead to an increase or decrease in the % of KOOS parameters (according to linear logistic regressions – **Table III**). This was also true considering two subgroups of cases in which the tunnel insertion site was outside and within the range recommended by ESSKA – no association was found between outside points (considered misplaced) and worse clinical outcomes in KOOS. However, a trend pattern can be identified in each subscale, through the orientation of the correlation lines. In all subscales, there was an inversely proportional relationship between t(%) and the clinical parameter (evidenced by a negative slope of the line), and a directly proportional relationship between h(%) and the clinical parameter (evidenced by a positive slope of the line) - **Figure 13** and **Figure 14**.

Similarly, no correlation between tunnel placement and threshold values for PASS in KOOS subscales was considered statistically significant, which means that the values of t(%) and h(%) did not cause the KOOS parameters to be below the cutoff values (according to binary logistic regressions – **Table IV**). According to threshold values for PASS in KOOS established by Muller *et al*.[38], only 48.78%, 63.41%, 29.27%, 34.15% and 43.90% of all patients considered their current knee state satisfactory, in terms of pain, other symptoms, ADL, sport/recreational activities and QOL, respectively, nevertheless this was not associated with femoral tunnel placement.

However, if we analyze the KOOS subscales separately by tunnel localization strategy, we observed that there was an almost statistically significant relationship (with a p-value of 0.052 for t(%) and 0.062 for h(%)) between the ADL Function subscale and the femoral tunnel placement using a freehand technique. That is, there was an inversely proportional relationship between t(%) and ADL Function and a directly proportional relationship between h(%) and ADL Function. No similar relationship was seen for offset aimers strategy (**Table V**).

Discussion

In this study, we hypothesized that a femoral tunnel placed nearer to the anatomical ACL position yield more favorable clinical outcomes in comparison to non-anatomically placed tunnel positions.

Regarding the imagiological evaluation of the surgical accuracy of femoral tunnel placement after ACL reconstruction, according to Bernard, the anatomical femoral tunnel insertion site is located at 24.8% of the total sagittal diameter of the lateral condyle measured along Blumensaat's line (deep-to-shallow distance or distance t(%)) and at 28.5% of the maximum intercondylar notch height perpendicular to Blumensaat's line (high-to-low distance or distance h(%)).[33]

In this study, as the mean t(%) value observed was superior to that considered anatomical according to Bernard *et al*.[33] (37.6% vs. 24.8%), this means that, on average, the insertion of the femoral tunnel was carried out in a shallower position, in comparison to the anatomical one. On the other side, as the mean h(%) value observed was inferior to that considered anatomical according to Bernard *et al*. (23.6% vs. 28.5%), this means that, on average, the insertion of the femoral tunnel was carried out in a higher position, in comparison to the anatomical one.

A shallower and higher position means that there was an excessive anterior placement of the femoral tunnel. And there is evidence that an anterior femoral tunnel insertion site leads to a verticalization of the tunnel (which has been associated with poorer clinical outcomes) and excessive tension in the graft in flexion (which could lead to graft failure).[39,40] Clinical and biomechanical research has shown that vertically placed grafts may effectively restore anterior tibial translation control, but exhibit less resistance to rotational loads compared to reconstructions with more horizontally oriented tunnels.[41] On the other side, recent biomechanical studies suggest that creating a femoral tunnel posteriorly on the lateral wall of the intercondylar notch can restore both anterior and rotational stability of the knee, leading to superior clinical outcomes.[14,42,43]

Regarding the influence of surgery-related factors on femoral tunnel placement, tunnel localization strategy chosen was considered statistically significant when taking into account specifically distance t (such statistically significant difference was not observed for distance h). Concretizing, in terms of deep-shallow distance along Blumensaat's line, the offset aimer strategy allowed a deeper (i.e., more posterior) tunnel insertion attachment, whilst through a freehand technique shallower (i.e., more anterior) insertion sites were obtained. So globally we can claim that better results were acquired using offset aimer devices, considering our goal that is to create a more posteriorly located femoral tunnel on the lateral wall of the intercondylar notch, although this only occurred in the deep-shallow direction and not in the high-low direction. Using an offset aimer facilitates drilling the femoral tunnel by leaning in the lateral condyle from posterior to anterior and places it at a fixed distance from the deep cartilage margin – the "offset" – typically used at 7 mm by the surgeon, to allow a posterior wall of only 2 mm for the tunnel when drilling a 10 mm diameter hole, which translates into a deeper placement. On the other hand, surgeons who use a freehand technique through anatomical references aim to place the center of the tunnel in the center of the conventionally defined "anteromedial" bundle, using the lateral intercondylar ridge as an anterior border and the lateral bifurcate ridge as a distal border, and typically drilling the tunnel from anterior to posterior, since this allows greater flexibility and adaptation to the patient's anatomical variations, and provides a more appropriate fixation. Recent studies have also demonstrated similar results where a more posterior positioning was achieved using offset aimers vs. freehand technique, contradicting their initial hypotheses.[44,45] It is also important to note that an extreme posterior positioning also carries risks, such as laxity and posterior wall blowout, and that in fact the point that we consider anatomical was given in 1997 when scientific knowledge was not as vast as it is today, therefore the current *gold standard* continues to be an anatomical ACL reconstruction, and we recognize that the freehand technique allows us to take into account the variability of each patient.

In terms of the coefficients of variation, the results obtained were very similar between offset aimers and freehand technique, and did not reflect the purpose of offset aimers, which is to standardize femoral tunnel placement (reducing variability and allowing consistent results). This means that the dispersion of the points occupied a similar area using one strategy or another; however, this area was located in a shallower position (i.e., more anterior) in the case of the freehand technique and this fact will be used below to explain the potential reason why using a freehand technique stronger correlations with clinical outcomes were made. One justification for this unexpected similarity of CV values and for its non-inferiority using offset aimers may be the confounding variable primary attending surgeon. Generally, those who opt for offset aimers are less experienced surgeons (since these devices help to standardize the tunnel insertion site) and therefore a technical superiority performed by more experienced surgeons may justify a similar or even, in this case, slightly lower CV using freehand technique, contrary to what was expected.

Focusing on the assessment of whether or not there are clinical implications of femoral tunnel placement through KOOS, unlike our initial hypothesis, no correlation was considered statistically significant and this was also true considering two subgroups of cases in which the tunnel insertion site was outside and within the range recommended by ESSKA – no association was found between outside points (considered misplaced) and worse clinical outcomes in KOOS. However, a trend pattern was identified in each subscale, through the orientation of the correlation lines: in all subscales, there was an inversely proportional relationship between t(%) and the clinical parameter, and a directly proportional relationship between h(%) and the clinical parameter. Although we cannot draw conclusions as it was not statistically significant, these trends are in line with the results of previous studies[26–30] that show a relationship between an insertion of the femoral tunnel that is too anterior - i.e., shallower and higher - and worse clinical outcomes (or a posterior insertion - i.e., deeper and lower - and better clinical outcomes). That is, as t(%) increases (as the center of the femoral tunnel insertion becomes shallower), the clinical parameter decreases (i.e., worsens), and as h(%) increases (as the center of the femoral tunnel insertion becomes lower), the clinical parameter increases (i.e., improves).

Although there was no statistically significant relationship between all femoral tunnel insertion points and KOOS subscales, this was almost true when analyzing only femoral tunnels performed using a freehand technique (which did not happen through offset aimers), in which there was an inversely proportional relationship between t(%) and ADL function and a directly proportional relationship between h(%) and ADL function, as expected. As mentioned before, a possible explanation for the correlation being stronger using the freehand technique may be related to the fact that the dispersion of the central insertion points of femoral tunnels was in a shallower position (i.e. more anterior), even though the CV was superimposable to that using offset aimers. This may cause these extreme shallow points to be associated with a worse KOOS, and since there are no such shallow points using offset aimers, not many differences were noticed in terms of KOOS and such strong correlation could not be established using this strategy. We also speculated that the two subgroups of patients who underwent different tunnel location strategies could be heterogeneous in terms of their anthropometric characteristics or other factors such as follow-up time, however, it was ensured that the groups were homogeneous and that differences of this type were not behind the results obtained.

The fact that in this study a statistically significant correlation was not found between femoral tunnel position and KOOS subscales when considering both tunnel localization strategies may have to do with several factors such as having a limited sample size (only 41 patients) that could have different characteristics and not be representative of a larger population, the subjectivity of KOOS itself (how much a patient values their symptoms is a personal experience) and also a potential confounding variable that is the follow-up time between the surgery and the KOOS assessment, which was not always the same. Regarding this last topic, it is known that longer follow-ups may not only be evaluating the direct outcome of the surgery, but also degenerative changes that naturally occur over time.[46]

Study limitations and future recommendations

A limitation of the study was the fact that the majority of patients who underwent ACL reconstruction surgery at our institution did not have a postoperative MRI, which reduced the total sample from 318 to 77 patients. In the same line of thought, not all operated patients had KOOS results available for consultation in the clinical record (only 41 out of 74).

The imaging test selected was MRI (a less harmful test than CT, since the patient is not exposed to ionizing radiation), which despite allowing good visualization of the neoligament, presents worse differentiation of bone structures.

As previosly mentioned, the fact that a statistically significant correlation between femoral tunnel placement and clinical results was not found in this study may have to do with several factors such as a limited sample size, the subjectivity of KOOS itself and also a potential confounding variable that is the follow-up time between the surgery and the KOOS assessment, which was not always the same - an analysis should have been done separately taking into account the follow-up time elapsed. Therefore, we recommend that these factors should be taken into account in the future and that a larger sample be obtained to improve this study.

Conclusion

In summary, this study allowed to evaluate the surgical accuracy of femoral tunnel placement after ACL reconstructions performed at our institution, demonstrating a rate of 71.6% of well-placed tunnels according to ESSKA consensus recommendations. Moreover, as several previous studies have demonstrated, a trend pattern was observed between a more posterior location on the lateral wall of the intercondylar notch and improved clinical outcomes evidenced by all KOOS subscales, albeit not being statistically significant. This underscores that there should be an effort to try to bring the femoral tunnel insertion site deeper (through Blumensaat's deep-shallow line) and lower (through intercondylar notch height). In this study, using offset aimers allowed a deeper (i.e., more posterior) tunnel insertion attachment, whilst through a freehand technique shallower (i.e., more anterior) insertion sites were obtained, contrary to the theoretical hypothesis that by not considering the individuality of each patient, offset aimer devices were more likely to lead to non-anatomical placements.

Appendix

Table I - Patients characteristics.

Age (years)	28.09 ± 10.31
Gender (F:M, %)	18:58 (21.6:78.4%)
Weight (kg)	76 ± 20 (48-149)
Height (cm)	174 ± 9
Body Mass Index (kg/m^2)	26.29 ± 6.49
Follow-up (years)	3.38 ± 1.42

Table II - Surgery characteristics.

		n	%
Tunnel localization strategy	Offset aimer	20	27.0%
	Freehand	54	73.0%
Graft structure	Hamstrings	62	83.8%
	Patellar tendon	4	5.4%
	Quadriceps tendon	7	9.5%
	Allograft	1	1.4%
Operated site	Left	33	44.6%
	Right	41	55.4%

Table III - Femoral tunnel placement distribution and Knee injury and Osteoarthritis Outcome Score (KOOS) - linear logistic regressions.

	HR (95% CI)	p-value
Pain (%)		
t (%)	-0.769 (-1.957; 0.418)	0.198
h (%)	0.821 (-0.480; 2.122)	0.209
Symptoms (%)		
t (%)	-0.156 (-1.141; 0.829)	0.750
h (%)	0.401 (-0.671; 1.473)	0.454
ADL Function (%)		
t (%)	-0.893 (-2.043; 0.257)	0.124
h (%)	1.104 (-0.144; 2.352)	0.081
Sport and Recreation Function (%)		
t (%)	-0.240 (-1.761; 1.282)	0.752
h (%)	1.111 (-0.517; 2.734)	0.175
Quality of Life (%)		
t (%)	-0.580 (-2.034; 0.874)	0.425
h (%)	1.164 (-0.395; 2.724)	0.139

Table IV - Femoral tunnel placement distribution and Knee injury and Osteoarthritis Outcome Score (KOOS) stratification by Patient Acceptable Symptom State (PASS) - binary logistic regressions.

	HR (95% CI)	p-value
Pain (%) (<89%)		
t (%)	0.964 (0.870; 1.068)	0.484
h (%)	1.058 (0.945; 1.185)	0.330
Symptoms (<58%)		
t (%)	0.995 (0.896; 1.104)	0.918
h (%)	1.034 (0.920; 1.162)	0.576
ADL Function (<100%)		
t (%)	0.921 (0.811; 1.045)	0.202
h (%)	1.050 (0.930; 1.185)	0.433
Sport and Recreation Function (<75%)		
t (%)	1.030 (0.927; 1.144)	0.586
h (%)	1.009 (0.898; 1.132)	0.886
Quality of Life (<63%)		
t (%)	0.944 (0.848; 1.052)	0.296
h (%)	1.031 (0.922; 1.153)	0.589

Table V - Femoral tunnel placement distribution and Knee injury and Osteoarthritis Outcome Score (KOOS) using freehand technique vs. offset aimers - linear logistic regressions.

	Freehand		Offset	
	HR (95% CI)	p-value	HR (95% CI)	p-value
Pain (%)				
t (%)	-1.142 (-2.598;0.314)	0.120	1.230 (-3.295; 5.755)	0.548
h (%)	0.923 (-0.642;2.488)	0.237	0.687 (-2.471; 3.845)	0.629
Symptoms (%)				
t (%)	0.099 (-1.109;1.306)	0.868	0.240 (-3.578; 4.058)	0.888
h (%)	0.168 (-1.105;1.441)	0.789	1.839 (-0.341; 4.019)	0.088
ADL Function (%)				
t (%)	-1.350 (-2.712; 0.013)	0.052	1.056 (-3.779;5.891)	0.628
h (%)	1.350 (-0.098; 2.798)	0.062	0.398 (-2.985; 3.781)	0.793
Sport and Recreation Function (%)				
t (%)	-0.694 (-2.560; 1.172)	0.255	2.360 (-3.452; 8.173)	0.376
h (%)	1.104 (-0.840; 3.048)	0.453	1.182 (-2.944; 5.309)	0.527
Quality of Life (%)				
t (%)	-1.013 (-2.765; 0.739)	0.247	-0.358 (-6.394;5.677)	0.894
h (%)	1.010 (-0.843; 2.864)	0.274	1.565 (-2.417; 5.547)	0.391

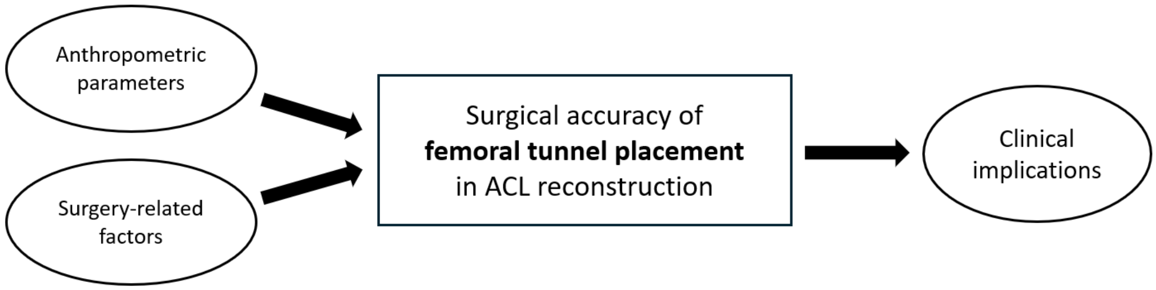


Figure 1 - Primary and secondary objectives of this study.

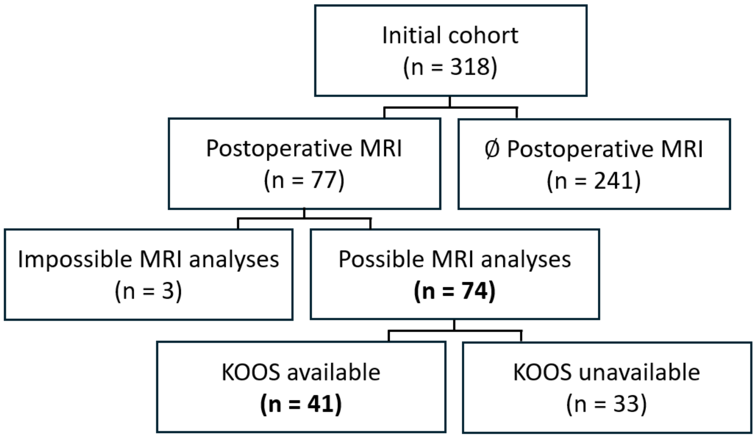


Figure 2 - Participant selection.
MRI: Magnetic Resonance Imaging; KOOS: Knee injury and Osteoarthritis Outcome Score.

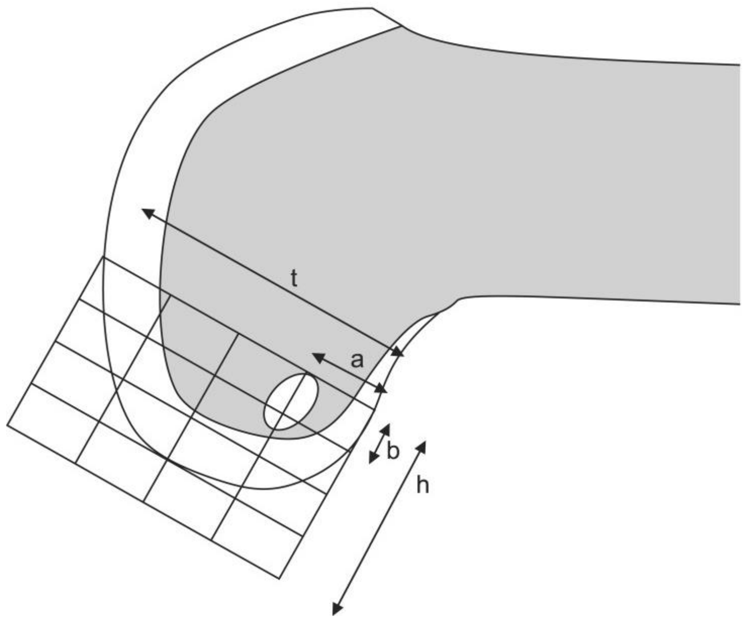


Figure 3 - Quadrant method by Bernard and Hertel.[33]

Figure 4 - Three sagittal MRI sections: a) displaying the roof of the intercondylar fossa of the femur (Blumensaat's line); b) showing the boundaries of the lateral condyle of the femur; c) presenting the femoral tunnel (first cut).

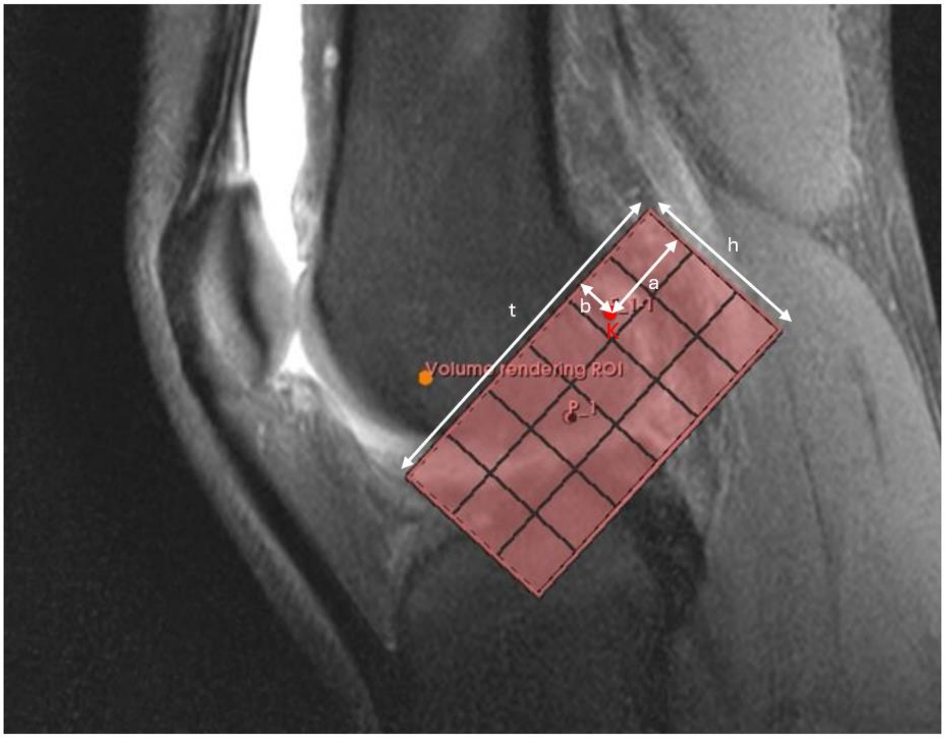


Figure 5 - Application of quadrant method, definition of point K and measurement of distances t, h, a and b.

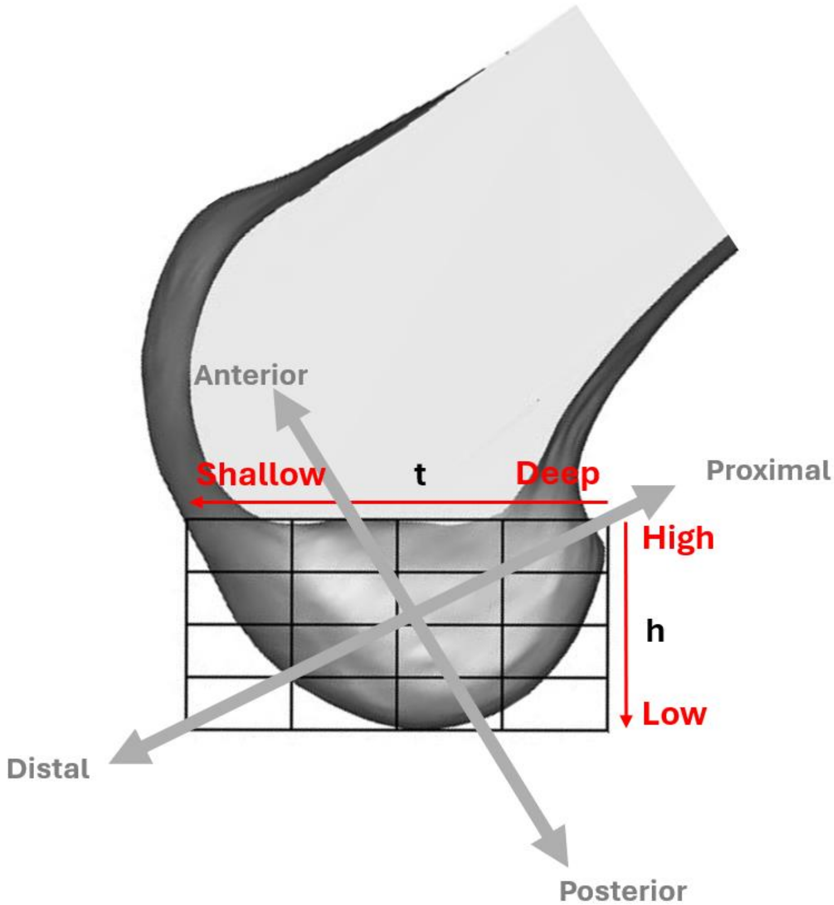


Figure 6 - Anatomical terms at the level of the lateral condyle of the femur.

Pain

P1 How often is your knee painful?	☐ Never	☐ Monthly	☐ Weekly	☐ Daily	☐ Always

What degree of pain have you experienced the last week when…?

P2 Twisting/pivoting on your knee	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
P3 Straightening knee fully	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
P4 Bending knee fully	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
P5 Walking on flat surface	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
P6 Going up or down stairs	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
P7 At night while in bed	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
P8 Sitting or lying	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
P9 Standing upright	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme

Symptoms

Sy1 How severe is your knee stiffness after first wakening in the morning?	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
Sy2 How severe is your knee stiffness after sitting, lying, or resting later in the day?	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
Sy3 Do you have swelling in your knee?	☐ Never	☐ Rarely	☐ Sometimes	☐ Often	☐ Always
Sy4 Do you feel grinding, hear clicking or any other type of noise when your knee moves?	☐ Never	☐ Rarely	☐ Sometimes	☐ Often	☐ Always
Sy5 Does your knee catch or hang up when moving?	☐ Never	☐ Rarely	☐ Sometimes	☐ Often	☐ Always
Sy6 Can you straighten your knee fully?	☐ Always	☐ Often	☐ Sometimes	☐ Rarely	☐ Never
Sy7 Can you bend your knee fully?	☐ Always	☐ Often	☐ Sometimes	☐ Rarely	☐ Never

Sport and recreation function

What difficulty have you experienced the last week…?

Sp1 Squatting	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
Sp2 Running	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
Sp3 Jumping	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
Sp4 Turning/twisting on your injured knee	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
Sp5 Kneeling	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme

Activities of daily living

What difficulty have you experienced the last week…?

A1 Descending	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
A2 Ascending stairs	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
A3 Rising from sitting	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
A4 Standing	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
A5 Bending to floor/picking up an object	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
A6 Walking on flat surface	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
A7 Getting in/out of car	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
A8 Going shopping	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
A9 Putting on socks/stockings	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
A10 Rising from bed	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
A11 Taking off socks/stockings	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
A12 Lying in bed (turning over, maintaining knee position)	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
A13 Getting in/out of bath	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
A14 Sitting	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
A15 Getting on/off toilet	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
A16 Heavy domestic duties (shovelling, scrubbing floors, etc)	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme
A17 Light domestic duties (cooking, dusting, etc)	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme

Knee-related quality of life

Q1 How often are you aware of your knee problems?	☐ Never	☐ Monthly	☐ Weekly	☐ Daily	☐ Always
Q2 Have you modified your lifestyle to avoid potentially damaging activities to your knee?	☐ Not at all	☐ Mildly	☐ Moderately	☐ Severely	☐ Totally
Q3 How troubled are you with lack of confidence in your knee?	☐ Not at all	☐ Mildly	☐ Moderately	☐ Severely	☐ Totally
Q4 In general, how much difficulty do you have with your knee?	☐ None	☐ Mild	☐ Moderate	☐ Severe	☐ Extreme

Figure 7 – Knee injury and Osteoarthritis Outcome Score (KOOS).

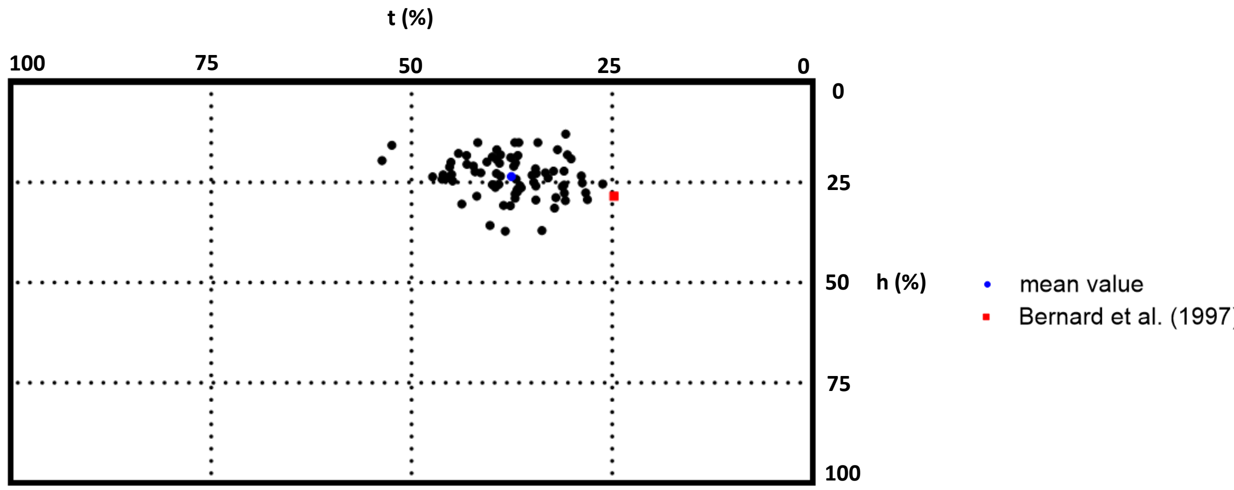


Figure 8 - Femoral tunnel insertion central points distribution.

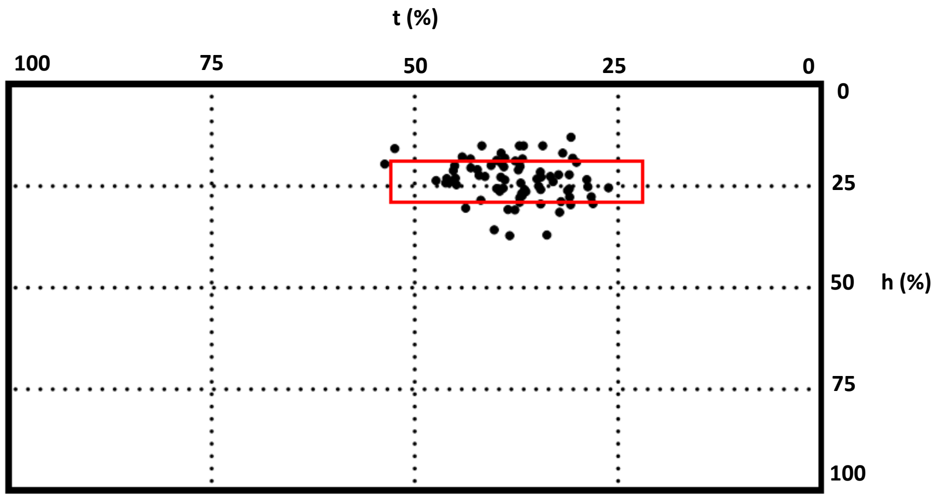


Figure 9 - Well and misplaced femoral tunnel insertion central points according to European Society of Sports Traumatology, Knee Surgery & Arthroscopy (ESSKA).[35]

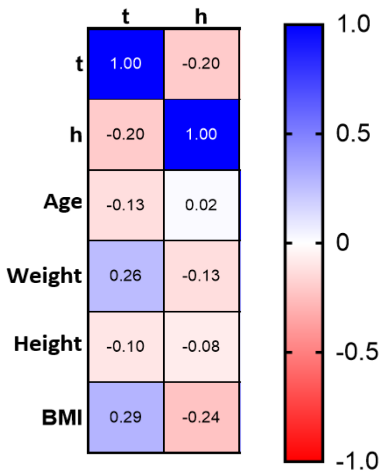


Figure 10 – Correlation between femoral tunnel insertion central points and anthropometric parameters.

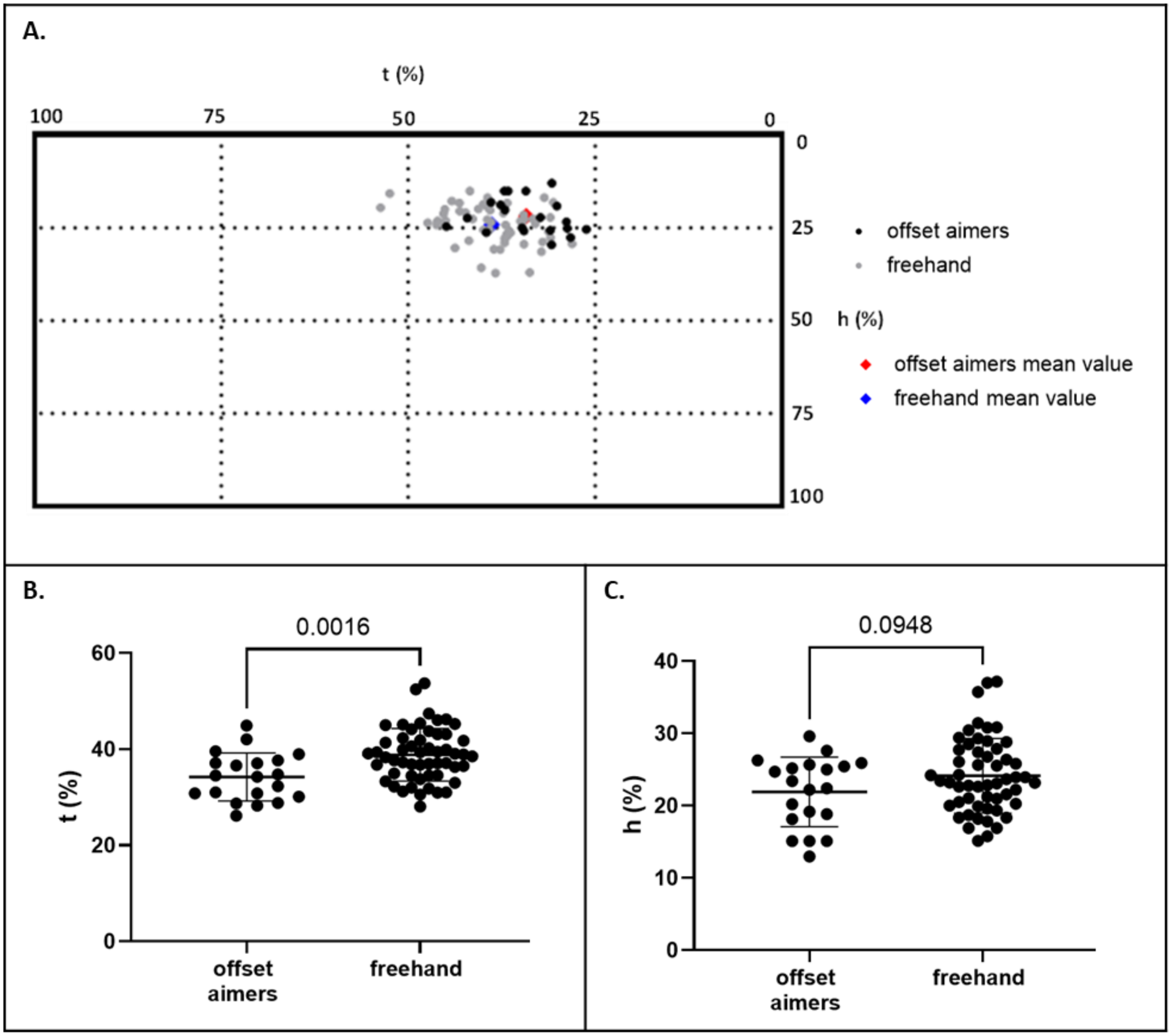


Figure 11 - A, B and C: Femoral tunnel insertion central points using offset aimers vs. freehand approach.

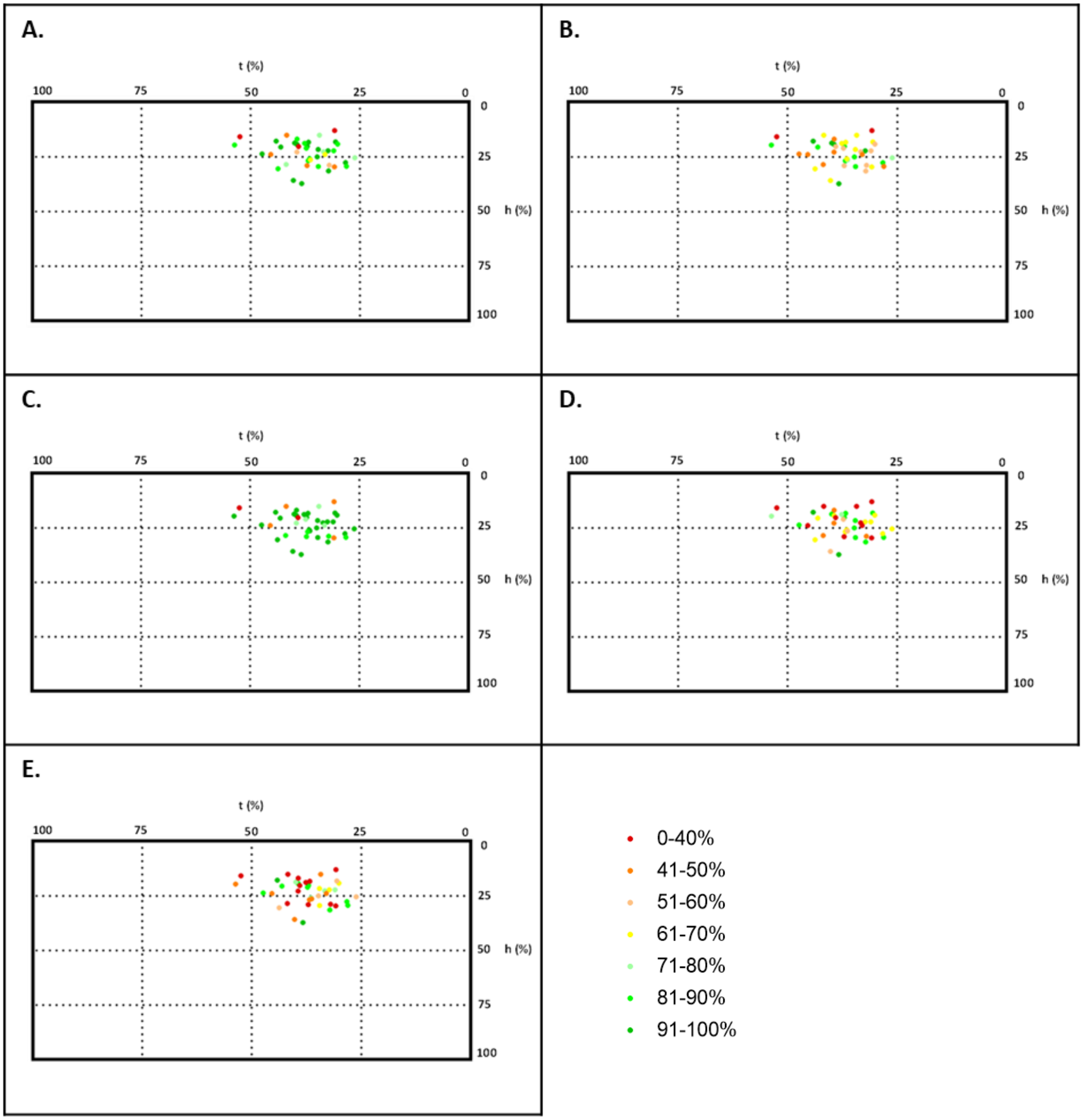
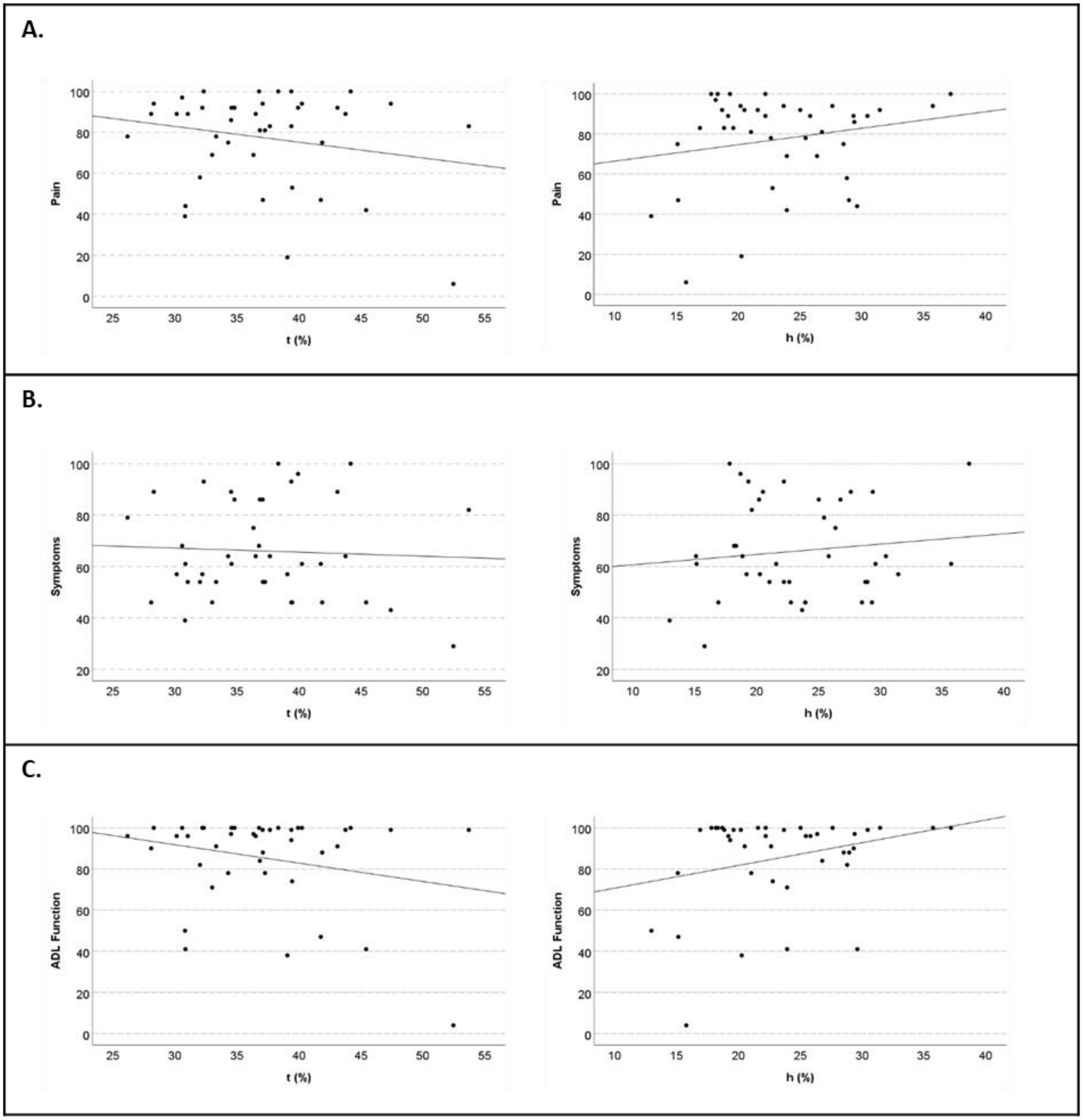


Figure 12 - Femoral tunnel placement distribution and Knee injury and Osteoarthritis Outcome Score (KOOS).
A. Pain; B. Other symptoms; C. Difficulty experienced during activities of daily living (ADL); D. Difficulty experienced during sport/recreational activities; E. Knee-related quality of life.


A.
Pain
t (%)
Pain
h (%)
B.
Symptoms
t (%)
Symptoms
h (%)
C.
ADL Function
t (%)
ADL Function
h (%)

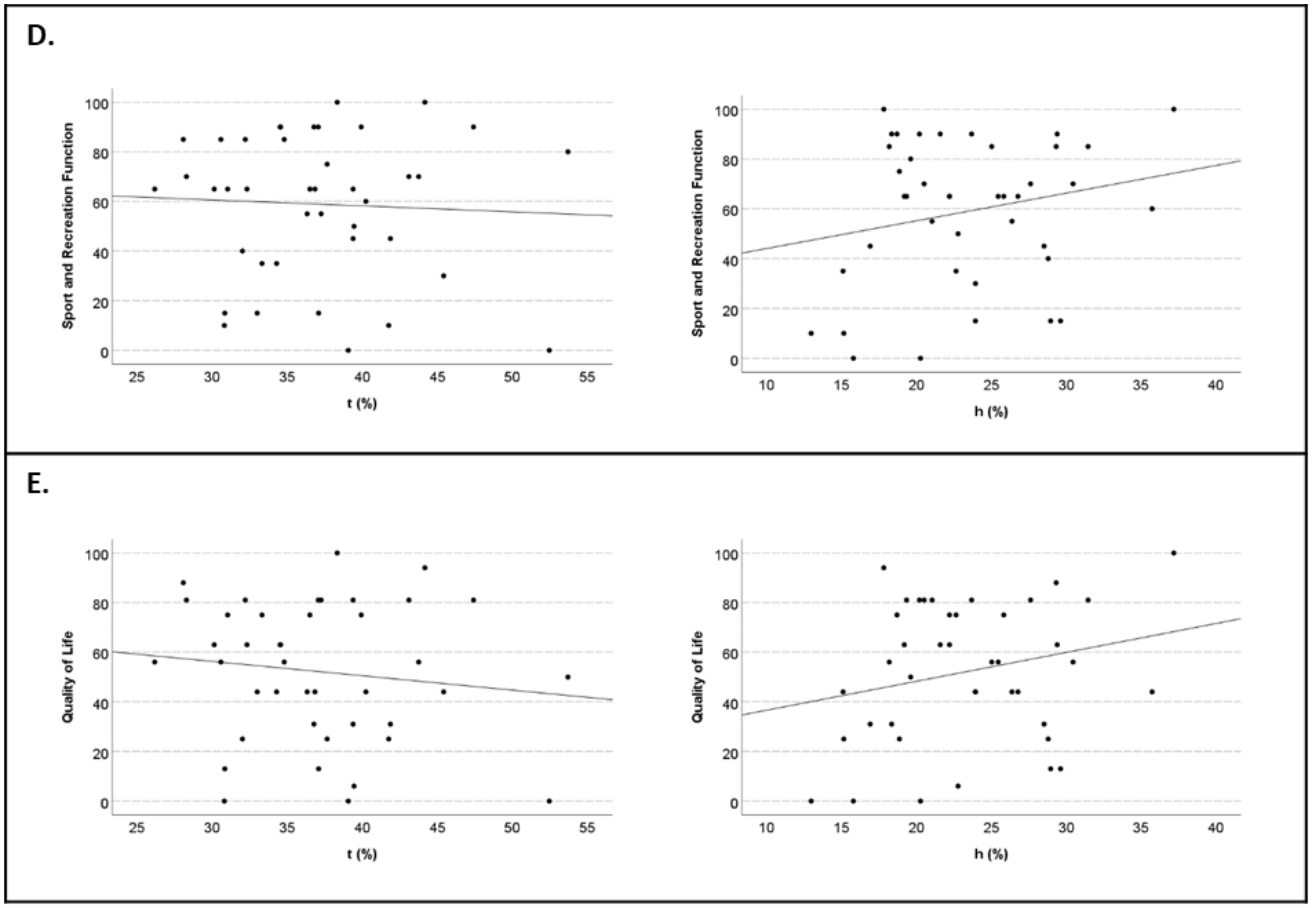


Figure 13 - Correlation between femoral tunnel placement distribution and Knee injury and Osteoarthritis Outcome Score (KOOS).
A. Pain; B. Other symptoms; C. Difficulty experienced during activities of daily living (ADL); D. Difficulty experienced during sport/recreational activities; E. Knee-related quality of life.

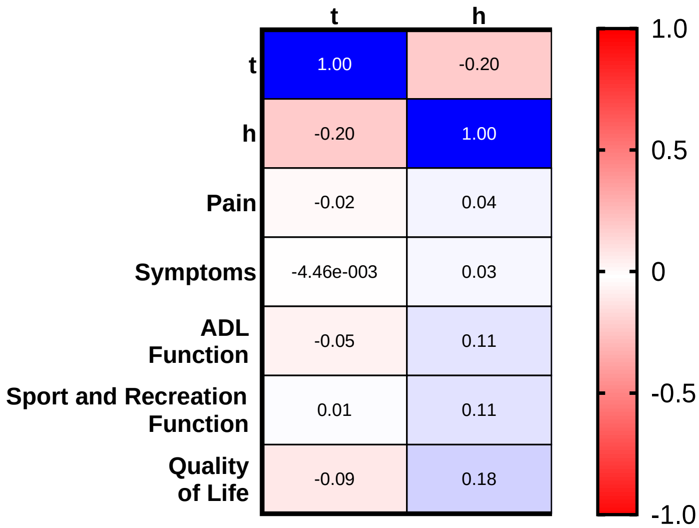


Figure 14 - Correlation between femoral tunnel insertion central points and Knee injury and Osteoarthritis Outcome Score (KOOS).
ADL: activities of daily living.

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