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RESEARCH ARTICLE

Is an x-ray of the knee sufficient to assess the alignment of the leg? A study of total joint replacement with surgical navigation.

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ABSTRACT

Background: Understanding the femorotibial mechanical axis (FTMA) of the leg is a necessary requirement to assess the outcome of total knee replacement (TKR). Short radiographs, which only capture the knee joint and do not include the center of the femoral head and center of the ankle, only provide us the anatomical axis (FTAA), and not the FTMA. The purpose of this study was to compare the FTMA and FTAA before and after navigated TKR.

Methods: In 130 patients undergoing surgery to implant the same TKR model, an x-ray was taken including the hip, knee and ankle. Images were analysed using a computer program that calculates the mechanical and anatomical axis of the femur, tibia and femorotibial joint. An image-free navigation system with femorotibial tensioned gap technique was used for the arthroplasty implantation. After surgery, a new long x-ray was taken, where the measurements indicated above were taken again.

Results: Pre-operative x-rays showed a mean difference of 6° between FTAA and FTMA ($p<0.001$). No significant interaction was seen with patient height, but it was in patients with varus deformity and higher BMI ($p=0.029$); the greatest discrepancy between the anatomical and mechanical axis of the limb was found in individuals with excess weight. After TKR, the mean FTMA was modified to achieve a neutral axis (180° ±3°), as well as a concentration of the figures that showed great pre-procedure disparity, which was verified by the difference in the pre- and post-operative SD (11.85 versus 3.13). The maximum difference between FTAA and FTMA, which stood at 18° before decreased to 5.5° post-TKR.

Conclusions: There is a major discrepancy between the FTAA and FTMA that increases when there is pre-operative varus deformity and in patients with excess weight. After TKR, the FTMA became concentrated, and the mean axis shifted towards the neutral axis. Performing x-rays that only include the knee is not useful for assessing the limb's alignment prior to or after TKR.

Abbreviations: FTAA=Femoro-tibial anatomic axis, FTMA=Femoro-tibial mechanical axis, TKR=Total knee replacement, SR= Short x-ray,LR= Long x-ray, BMI= *Body mass index,* FMA=Femoral mechanical axis, FAA= Femoral anatomic axis.

Keywords: Total knee replacement; short x-ray; long x-ray; mechanical alignment; femoro-tibial axis; varus deformity; valgus deformity.

1.Introduction

The good medium- and long-term results obtained with total knee replacement (TKR) are known, with survival of over 96% at 15 years[1]. It may even be suggested that, with the advances made in materials over the last twenty years, these percentages will continue to increase in the future. However, a significant number of patients who are not satisfied with this procedure remain[2]. It is possible that the patient has higher expectations about the result of this procedure and expects more in terms of functionality of the knee and return to normal life, but nevertheless, extensive literature has investigated the cause of these poor results, revealing multiple reasons[3]: one of personal responsibility of the patients themselves, others related to implant design or materials, and others of direct responsibility of surgeons to implant the arthroplasty.

Malalignment among the latter group has been strongly claimed[4], and is, in fact, considered to be a frequent cause of short- and medium-term failures, particularly when TKR has been placed with a varus angulation[5-7]. That is why it has been considered that achieving a correct alignment of the implant following the axis of the leg is an inexcusable objective of this frequent procedure. This correct alignment facilitates the neutral transmission of loads, prevents asymmetric wear of the prosthesis and improves the functional result.

Throughout the history of TKRs, various alignment systems have been recommended, such as the relationship between the position of the arthroplasty and the resulting axis of the lower limb. Alignment along the mechanical axis of the limb (from the center of the femoral head to the center of the ankle) has been the most widely used to date and is considered the closest to physiological alignment in the standing position. Other types of alignment, such as the so-called kinematic alignment, have not yet demonstrated better clinical outcomes than mechanical alignment and now represent a controversial option[8] .

Both in the pre-operative study and in the evaluation of TKR results, a plain x-ray is commonly used in anteroposterior and lateral views capturing the lower end of the femur and the upper end of the tibia. This short radiograph (SR) may be useful for viewing local implant complications or gross surgical technique defects, but it is not useful for the calculation or monitoring of the limb axis, which can only be achieved by marking the center of the femoral head and of the ankle, which, therefore, is only possible with long radiographs (LR) o CT capturing the entire limb. Despite this known limitation of SR, it is common for this type of x-ray to be used in the literature to evaluate the technique, results, and follow-up of this procedure.

Conventional manual instrumentals attempt an adequate approximation of the bone resections necessary to achieve a neutral mechanical alignment (180°±3° between the femur and tibia axes). But these instrumentals have shown a high rate of errors in the placement of the knee prosthesis. In recent years, however, surgical support systems such as navigation, individualized templates or robotics have been developed to avoid coronal, lateral or axial malpositioning. The emergence of these techniques, which try to prevent outliers resulting from manual instrumentation, precisely indicate the importance attributed to correct alignment in the future of arthroplasty.

The objectives of our study are: 1.- To find the difference and concordance between the anatomical and mechanical axis of the femur, tibia and lower limb in the pre-operative LR, 2.-To verify whether these differences are modified depending on variables such as prior deformity of the limb axis, body mass index (BMI) or the height of the patients and 3.-To analyse the LR after navigated-TKR to determine the modifications arising in the limb axis after this procedure, comparing these findings with the pre-operative radiographic study.

2.Methods

This is a prospective, non-randomized study of 130 cases, 86 women and 44 men, in whom the same cemented TKR model was implanted (Apex TKR, Corin Group, Gloucestershire, UK); in 13 cases it was bilateral. The right knee was operated on in 69 cases and the left knee in 61 cases. Inclusion criteria were those cases that had a short and long X-ray performed before and after TKR and in which the measurement of the femoral, tibial and leg axes could be performed.

2.1. Pre-op measurements

Before surgery, all patients had lateral and frontal LR, including the femoral head, knee, and ankle. This radiograph was performed in complete extension of the knee, with the patella centered, and included a known diameter marker for accurate measurement of angles, distances and size of bone structures. The radiograph was discarded, and the case excluded from the study if it did not meet the described requirements for adequate performance of this projection[9-10]. From the PACS (Picture Archiving and Communication System) and using Impax software (Version 6.3.1. 2813, Agfa

Healthcare N.U. Montsel, Belgium), images were analysed using an orthopedic imaging program (Agfa Orthopaedics Tools v 2.06) to proceed with surgical planning. This tool was used to calculate in the coronal plane the femoral anatomical axis (FAA), femoral mechanical axis (FMA), tibial anatomical axis, tibial mechanical axis, femorotibial anatomical axis (FTAA) and femorotibial mechanical axis (FTMA). The software facilitates the drawing of the lines and specifies the angulation obtained in degrees. To measure FAA, the middle of the femur was marked immediately below the lesser trochanter, and at the center of the knee joint surface level. For the anatomical axis of the tibia, a line was drawn from the center of the tibial joint surface to the center of the ankle according to references published by Moreland et al.[11]. The FTAA was obtained at the intersection of the FAA and tibial axis. To measure the FMA, we marked the center of the femoral head located using digitized concentric circles and the center of the femoral condylar region; for the mechanical axis of the tibia, the same references as those already described for the anatomical axis were marked[12]. The FTMA was determined with the intersection of the FMA and the tibial axis (Figure 1).

Figure 1. Pre-operative measurement of FTAA and FTMA in long radiography. FAA: 82.1°, FMA: 90°. Anatomical and mechanical tibial axis: 91°

2.2 Surgical technique

All surgical procedures were performed using the same technique and navigation system (Nanostation,Total Knee Surgetics, Praxim, S.A., La Tronche, France). The navigation system used does not use previous images; it finds the center of the femoral head and gathers the bone landmarks using femoral and tibial mapping. Among other characteristics, it shows the mechanical axis of the limb along the entire range of motion and provides guidance on the size of the medial and lateral femoral-tibial space. The femorotibial tensioned gap technique was used in all cases, performing the necessary navigation-controlled releases until a neutral limb axis was achieved.

2.3 Post-op measurements

Between 10 and 30 days after TKR, another LR was performed with the same technique, and the previously described measurements were repeated. All measurements were performed by two of the authors who had extensive experience with the software for collecting and measuring radiographic images. Positive angulation was considered a varus deformity, while negative angulation was considered a valgus deformity.

All patients were informed and agreed to participate in the study, which was approved by the Regional Ethics Committee (PI12/01098).

2.5 Statistical analysis

The statistical analysis was performed using SPSS 23.0 software and Med-Calc version 9.3.1. All variables were studied descriptively. The Student's t-test was used for paired samples, the Kolmogorov Smirnoff test was used to verify normality of the differences and the general linear model of repeated samples was used to determine the interaction of preoperative axis, height and BMI with differences in measurements.

3.Results

The mean age of the patients was 71 years. Mean BMI was 31.1, and mean height was 158 cm (Table 1).

	Age	Height (cm)	BMI
Mean	71.07	158	31.1
Max	88	187	52.3
Mín	41	135	20.9
SD	9.57	0.11	5.52

Table 1. Patient demographics

In the pre-operative measurement, mean FTAA was 178.57°, and FTMA was 184.61° ($p<0.001$). A mean difference of 6.04° was therefore seen, with a correlation of 0.958. Mean FAA was 82.84° and FMA 88.73° ($p<0.001$), with a difference of 5.89° and a correlation of 0.680 (Table 2).

	FTAA	FTMA	FAA	FMA
Mean	178.57	184.61	82.84	88.73
Max	202.5	220.3	99.9	98.7
Min	149.8	157.8	71	78.1
SD	11.86	11.85	5.0	4.26

Table 2. Pre-operative angulations (°).

The cases were divided into three groups according to pre-operative deformity per the FTMA (neutral: 180°±3°, varus: ≥184°, and valgus: ≤176°); thirty-eight cases were classified as valgus, 11 neutral and 81 varus. In the valgus knee group, mean FTMA was 168.89° and mean FTAA 162.23°. In the group of knees with neutral axis, the mean FTMA was 180.28° and mean FTAA 174.89°; in the group of varus knees, the mean FTMA was 192.28° and mean FTAA 185.99°. The difference between the mechanical and anatomical axis of the limb was greater in varus cases, though the differences were statistically significant in all three groups (Figure 2).

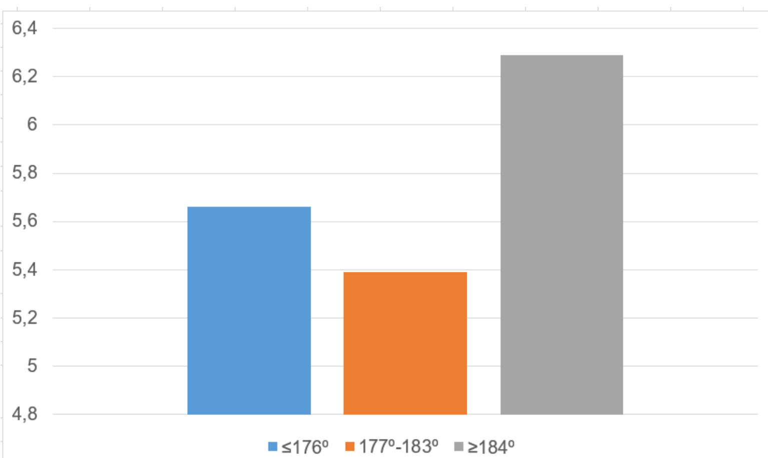

Figure 2. Difference between mean FTAA and mean FTMA depending on pre-operative limb angulation

The correlation between FTMA and FTAA was 0.785 valgus, 0.726 neutral, and 0.862 varus. Differences were also significant for the femoral axis, except for patients with a neutral axis; correlation was 0.578, 0.304, and 0.575, respectively (valgus, neutral, and varus deformities) (Table 3).

Preoperative axis	n	FTAA-FTMA		FAA -FMA	
		Mean differences	p	Mean differences	p
≤176°	38	5.6568	<0,001	5.8263	<0.001
177°-183°	11	5.3889	<0.001	4.2000	0.103
≥184°	81	6.2889	<0.001	6.1111	<0.001

Table 3. Differences between FTAA and FTMA and between FAA and FMA depending on pre-operative axis.

Differences between FTMA and FTAA were also analysed in terms of patient height and BMI. No significant interaction was seen with height in the overall series (p=0.386), or breakdown of patients into three groups according to height (<153 cm, 153-170 cm and >170 cm). On comparing the FMA or FAA measurements, including the variable BMI as covariate in a general linear model, this variable showed interaction with the difference in anatomical versus mechanical measurement (p=0.029). The same analysis dichotomizing the BMI variable between patients with normal weight (18 cases) vs pre-obese or obese (112 cases) had a significant interaction (p=0.043). Greater discrepancy was observed between the mechanical and anatomical axis in individuals with obesity or pre-obesity, mainly at the expense of measuring the mechanical axis.

The same measurements already described were performed after TKR (Table 4).

	FTAA	FTMA	FAA	FMA
Mean	175.8	182.32	84.37	90.1
Max	189	194.5	98.9	95.7
Min	165	174	73.8	80.6
SD	4.10	3.13	4.30	2.37

Table 4. Post-operative angulations (°)

The mean FTAA was 175.8° and the mean FTMA was 182.3°, with a difference of 6.5° and between FMA and FAA of 5.7°. Both differences were statistically significant (p<0.001). This same significance was obtained by separating patients according to the three groups of pre-operative deformity described above (Table 5).

Postoperative axis		**FTAA-FTMA**		**FAA - FMA**	
	n	Mean differences	p	Mean differences	p
≤176°	5	7.4200	<0.001	9.7000	0.001
177°-183°	90	6.5225	<0.001	5.5261	<0.001
≥184°	35	6.4000	<0.001	5.6647	<0.001

Table 5 Differences between FTAA and FTMA and between FAA and FMA depending on post-operative angulation (°).

Comparison of pre- and post-operative measurements showed that after navigated TKR, the mean FMA achieved was 90° and the mean FTMA was modified to achieve a neutral axis (180°±3°) (Figure 3); cases with neutral axis increased from 11 to 90.

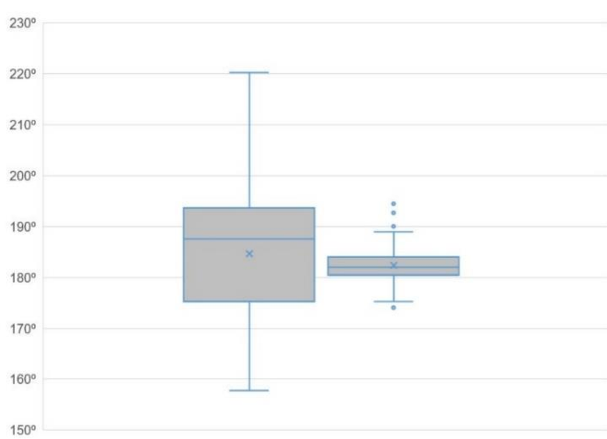

Figure 3. FTMA modification after TKR

The pre-operative angulations of the mechanical axis of the limb that presented great disparity were also found to concentrate after the procedure, as shown by the difference in SD between both (11.85 versus 3.13). Likewise, in the mean pre-operative

FTAA, the range between maximum and minimum angulation was 52°, and in the FTMA 36°. After TKR, the range becomes 24° and 12°, respectively (Table 6).

	FTAA Mean (SD)	FTAA Range	FTMA Mean (SD)	FTMA Range
Preoperative	178.57° (11.86)	52°	184.61° (11.85)	36°
Postoperative	175.8° (4.10)	24°	182.32° (3.13)	12°

Table 6. Pre- and post-operative differences between FTAA and FTMA.

The maximum difference between the FTAA and FTMA of 18° in the pre-operative study decreased to 5.5° in the post-operative (Figure 4), which shows that navigation was able to concentrate and homogenize the angular amplitude of the axes.

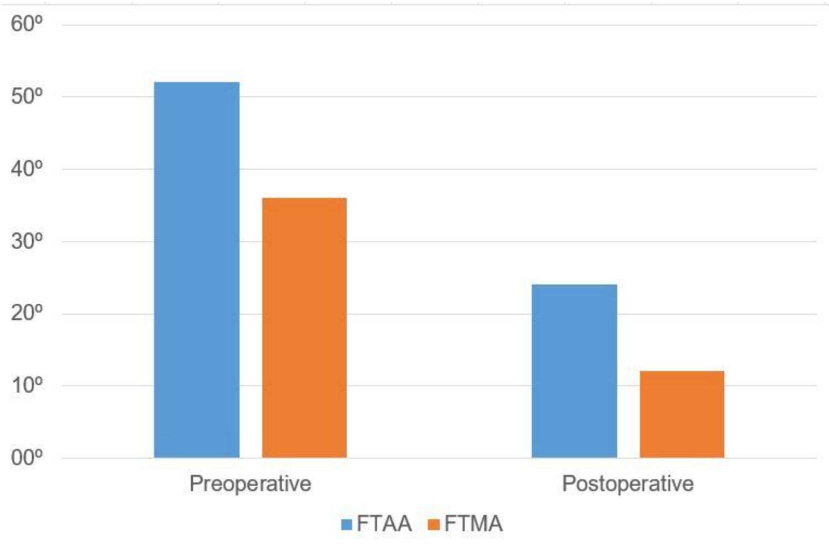

Figure 4. Pre-operative to post-operative FTAA and FTMA range

4.Discussion

Our results show that the mean difference between the mechanical and anatomical axes of the limb was 6°. We have observed the great disparity between the two axes, which in some patients reached 18° and was greater when the preoperative knee deformity was varus. These differences were not related to patient height, but were related to BMI, finding a greater discrepancy between the mechanical and anatomical axes in individuals with excess weight. After TKR it was observed that the angulations of the mechanical axis of the limb clustered, with the mean FTMA in the neutral axis, and that the maximum difference between the FTMA and FTAA decreased from 18° to 5.5°.

Obtaining correct limb alignment has been considered a necessary requirement to achieve good clinical results after TKR[13]. At the start of this procedure, the limb axis was obtained from the intersection of the anatomical axis of the femur and tibia. The concept of mechanical axis was later introduced, considering as references the center of the femoral head, center of the knee and center of the ankle, thus recreating an ideal axis in the coronal plane of 180°±3°[14-16]. The various surgical techniques have sought neutral mechanical alignment and may be considered one of the key premises for adequate TKR placement. The design of conventional instruments allows for placement of the femoral component of the arthroplasty between 2° and 8° valgus, although some authors recommend extending this angulation to 12° based on the difference between FMA and FAA found in some studies[17-19]. If the position of the center of the femoral head and ankle is not known and, therefore, the mechanical axis of the limb is ignored, the instrumentation is being used randomly according to what the surgeon has subjectively decided, and it can be said that the patient is being adapted to the instrumentation and not the instrumentation to the patient, as would be advisable. Obviously, this can lead to errors, especially in complex knees with deformities. This difficulty is present both in the study of the pre-operative axis and the axis obtained after arthroplasty.

The radiographic study in two projections performed with SR are part of the standard pre-operative study and periodic post-operative evaluation of this procedure. The SR plate is conventionally 30 by 40 cm in size, and it includes the lower femur and upper tibia[20]. This makes it impossible to know the mechanical axis of the limb, which is only possible by performing a LR, a CT, or using techniques such as navigation[21] or individualized templates[22]. Of note in the literature is the publication of results of TKRs based only on SR where complications of other types can be seen but are never related to the axis of the limb[23-27]. Even in the most used clinical and functional questionnaires after TKR, SR is recommended as a support technique when post-operative limb alignment, rather than knee alignment, should be an essential piece of data for understanding the results and predicting potential complications[20]. The practice of LR certainly involves greater costs, specialized radiological equipment and a higher dose of radiation for the patient, but its absence weakens the evaluation of the technique and the outcomes of this procedure.

Since the need to know the mechanical axis of the limb pre- and post-operatively is accepted, attempts have been made to predict this axis from the anatomical axis. Although automated systems have been described to measure the mechanical axis from a SR[23], this is only possible if there are no deformities in the femur or tibia as a result of fractures, previous surgery or other progressive degenerative processes.

There is little literature on the possible relationship between patient characteristic, such as BMI, height, or previous deformity, and the difference between the anatomical axis and the mechanical axis. Various predictors have been defined, including FTAA, FAA and patient height. The latter was a strong predictor for finding the mechanical axis of the limb, but, even if these factors were considered associated, the FTMA was only predicted in 61% and 63% of men and women, respectively[28]. According to our results, the height of the patient was not a determining and differential factor, but the BMI was, which had not been described until now, since in patients with excess weight the discrepancy between FAA and FMAs was greater than in patients with normal weight. We do not know the cause of this difference.

The literature reports highly variable correlation figures between FTAA and FTMA ranging from 0.26 and 0.93 [23,29]. This correlation further decreases when the pre-operative axis presents a varus or valgus deformity, which is common in patients who qualify for TKR. Furthermore, it is not uncommon for knees with a varus axis in the SR to become valgus in the LR or vice versa[30] with the corresponding potential significance for the joint replacement implantation. Other studies that found a low correlation between FTAA and FTMA have found that the fact of starting from a varus, valgus or neutral axis has discordant ranges ranging from 15° to 70°[20]. Graden et al. [31] published a correlation of the FTMA measured in SR and LR of 0.72 with a mean difference of 4.4°, observing that in the 80% of patients, the difference was greater than 2°. Park et al. [25] found that in the pre-operative study, 14% of the cases had a neutral axis in SR, but 50% had varus or valgus deformity when the same cases were studied with LR. The same study found that after TKR, 51% of the patients had a neutral axis in SR, but 27% of them presented varus or valgus angulation when LR was performed. We are not aware of any studies analysing FTAA and FTMA modifications after TKR, as we did in our study. After implantation, performed using navigation, we obtained an improvement in the mean FTMA that became neutral, which supports the use of this technique in the search for the correct axis. In addition, the differences between FTAA and FTMA were lower than in the pre-operative period (at most 5.5°, very different from the 18° before surgery). The angulations obtained were more homogeneous, as seen by the difference in ranges and SD. Navigation has therefore made it possible to reduce the degree of dispersion and achieve a neutral mechanical axis. Recent meta-analyses[32] have shown that navigation increases the safety and consistency of implant position, and that this has a beneficial effect on clinical and functional outcomes. This technique reduces asymmetric polyethylene wear, mobilization and sinking in of prosthetic components, particularly in young and active people, and prevents complications derived from the use of manual instrumentation [33-35]. As an added benefit, navigation may make the pre- and post-operative LR unnecessary, because the mechanical axis of the femur, tibia and limb can be obtained by finding of the center of rotation of the femoral head and the determination of bone landmarks.

Our paper has certain limitations. First, this is a series of patients where varus and valgus deformities are common. This is because navigation was indicated in our series precisely because of these deformities and the presumable difficulty in obtaining correct alignment with conventional surgical techniques. Second, this is a study exclusively conducted with radiographic studies, and no assessment is made of the clinical condition or functional results after the procedure.

Radiographic axes and clinical outcomes cannot be directly linked, but it can be absolutely accepted that obtaining correct limb alignment is an essential requirement for implant survival. Thirdly, we referred exclusively to mechanical alignment achieved by navigation. Our findings cannot be extrapolated to other types of alignment or to other surgical techniques used to implant a total knee arthroplasty.
According to our results, the anatomical axis of the leg obtained with a short X-ray cannot be equated with the mechanical one, the true axis of the limb, which is only obtained with CT or long X-ray. The discrepancy increases when there is pre-operative varus deformity and in patients with excess weight. These findings reinforce the idea that a standard knee radiograph is not useful for evaluating the limb axis after TKR and can only be achieved with a radiograph showing the center of the femoral head and the center of the ankle.

5.Conclusions

TKR is one of the most common procedures in orthopaedic surgery. However, the lack of knowledge of the pre-operative angulation of the mechanical axis of the limb introduces a confounding factor in its surgical technique. Standard x-ray examination using a short x-ray cannot replace a full x-ray of the leg, as there are major discrepancies between the anatomical and mechanical axis of the limb. Similarly, an x-ray that does not show the femoral head and ankle cannot be used to determine the alignment result obtained after TKR.

Authors' contributions

DH-V initiated the study, wrote, and reviewed the manuscript, AN-F collected data and performed radiographic measurements, JMF-C performed statistical analysis, SR-G performed radiographic measurements. All authors have read and approved the final manuscript.

Conflicts of Interest

The authors have no conflicts of interest to declare.

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Ethics approval and consent to participate

The study was conducted according to the principles of the Helsinki Declaration and was approved by the regional ethical committee in Oviedo, Spain (PI12/01098).

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