Coronal and sagittal alignment of the lower limb in Caucasians: Analysis of a 3D CT database

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Original article

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Abstract

Introduction: Lower limb alignment is a major determinant of long-term outcomes after osteotomy or total knee replacement. The aim of this paper is to define the mean values of coronal and sagittal lower limb alignment for Caucasians as a function of sex using 3D reconstructions from CT scans.

Materials and methods: The analysis involved 586 Caucasian patients (269 males and 317 females) who had their hip-knee-ankle angle (HKA), lateral distal femoral angle (LDFA), medial proximal tibial angle (MPTA), posterior proximal tibial angle (PPTA), lateral and medial proximal posterior tibial angles (LPPTA / MPPTA), posterior distal femoral angle (PDFA), and non-weightbearing joint convergence angle (nwJLCA) measured. This analysis was performed using a CT scan-based modelling system (SOMA). Differences between sexes and morphotypes (neutral, varus and valgus) were analyzed statistically.

Results: The mean HKA was 180 ± 2.57°, LDFA 86.1 ± 1.87°, MPTA 86.1 ± 2.15°, PPTA 84.6 ± 2.58°, LPPTA 84.9 ± 3.17°, MPPTA 85.1 ± 3.21°, PDFA 85.3 ± 1.50° and nwJLCA 0.82 ± 1.32°. There was a significant difference between sexes for the HKA (180.3 ± 2.46° and 179.0 ± 2.52°), LDFA (85.6 ±1.90° and 86.8 ± 1.61°), MPPTA (84.7 ± 3.06° and 85. 6 ± 3.31°). The neutral morphotype was more frequent in women than men (78% vs. 73%), the varus morphotype was more frequent in men than women (20% vs. 7.6%) and the valgus morphotype was more frequent in women than men (15% vs. 6.7%).

Conclusion: Normal parameters for lower limb alignment in Caucasian patients were described in the coronal and sagittal planes. There was a significant influence of sex in the coronal plane, which was not found in the sagittal plane.

Level of evidence: IV; retrospective cohort study

Keywords: Alignment, knee, native, lower limb, CT, HKA, MPTA, LDFA, PPTA, JLCA, 3D

Introduction

Performing joint preservation or knee replacement surgery requires a good definition of the potential abnormality in lower limb alignment and just as importantly, the target for normal alignment [1-5].

Thanks to our improved understanding of anatomy [6], correction of alignment defects in the lower limbs underwent a revolution in the early 21st century with changes in how the correction objectives are defined [7-8].

In parallel, osteotomy procedures are now more accurate because we have a better understanding of its effect in all three planes in space and have better surgical aids [9-11].

This correction requires precise objectives in terms of the coronal and sagittal alignment. While these have been described in the scientific literature, they were based on 2D analysis in small patient populations [6]. This analysis is affected by the acquisition parameters due to incorrect limb rotation or the presence of a flexion deformity, which modify the alignment in the coronal plane. The sagittal alignment is also difficult to analyze in two dimensions [12].

The use of 3D images reconstructed from CT scans allows for a morphological analysis of the lower limbs in a precise and reproducible manner, getting around errors associated with 2D analysis, both in the coronal and sagittal planes [12-13]. Thanks to these methods, Hirschmann et *al.* [13] identified 43 potential functional phenotypes for lower limb alignment. This large disparity casts doubt on the concept of a normal anatomy or neutral alignment, which was rarely present in their study population [13]. It has also been shown that this alignment was significantly different between ethnic groups [14-15].

The aim of our study was to define the mean values of coronal and sagittal alignment in the lower limbs for Caucasians. We hypothesized that this alignment varies with sex and functional knee phenotype.

Materials and Methods

For this study, the analysis was done using a modeling and analysis system created for CT scan images (SOMA, Stryker®, Mahwah, New Jersey) [16]. This database was developed to evaluate demographic variations. The SOMA database contains more than 25,000 bone models obtained from more than 3600 patients throughout the world. All the CT scans were performed while complying with local legal and regulatory requirements, namely ethics committee approval and informed patient consent. These CT scans were made solely for medical indications such as polytrauma (20%), CT angiography (70%) and other reasons (e.g., total knee replacement) (10%). More than 3,500 individuals who did not have any obvious osteoarthritis, fracture or joint and bone lesions were extracted from the SOMA database. Among these, 586 records (269 male records and 317 female records, mean age 61.9 $\pm$ 15 years, mean BMI of 25.6 $\pm$ 4.6 kg/m^2) had reliable images with a complete set of measurements and were Caucasians (White Americans of European origin).

This system makes it possible to analyze the pelvis and femurs, tibias and patellae in a bilateral manner. Subjects with a bone or joint abnormality, advanced osteoarthritis or signs suggestive of prior surgery were excluded during an initial radiographic screen, before the CT images were selected. The hip-knee-ankle (HKA) angle, lateral distal femoral angle (LDFA), medial proximal tibia angle (MPTA), posterior proximal tibial angle (PPTA), posterior distal femoral angle (PDFA) and the non-weightbearing joint line convergence angle (nwJLCA) were calculated for each knee (Figure 1).

All the measurements were made on each bone in the database by the automated software, which provided precise reproducible values for each subject, with an error margin of < 2 mm and < 1° [17-18]. Using a previously described method [15], the HKA, LDFA, MPTA, PPTA, PDFA, nwJLCA angles were calculated. The HKA angle was defined by lines between the center of the femoral head, knee and ankle joints. The distal femoral axis was then created from the most distal points on the medial and lateral femoral condyles. The LDFA was determined by the angle between the distal femoral axis and the mechanical axis in the coronal plane. The proximal tibial plane was created by fitting 35 points on the medial and lateral tibial compartments. The intersection between the proximal tibial plane and the tibial axis, between the tibial center of the knee and tibial center of the ankle was then determined as the MPTA in the coronal plane and the PPTA in the sagittal plane. The LPPTA was defined by calculating the PPTA with the lateral tibial plateau as a reference; for the MPPTA, the medial tibial plateau was used as a reference. The posterior angle between the femoral sagittal axis joining the anterior and posterior points on the femoral condyles and the sagittal femoral mechanical axis was defined as the PDFA. The nwJLCA was defined in the coronal plane as the joint line convergence angle joining the distal femoral axis and the proximal tibial plane.

Various functional knee phenotypes have been defined by Hirschman et *al*. [13]. The mean differences between each angle value and morphotypes (neutral, varus or valgus alignment) between sexes (male, female) were analyzed. Knees were considered as having an inherent varus (Var) if the HKA angle was less than 177°; neutral (NA) if the HKA angle was between 177° and 183° or an inherent valgus (Val) if the angle was more than 183°.

Statistical analysis:

Mean and standard deviation (SD) values were determined for each of the measurements done on the population. A univariate analysis was done using Student's *t* test to estimate the difference between groups for the quantitative variables and a Chi^2 or Fisher test for qualitative variables. An ANOVA was used to compare the three alignment groups. A p value < 0.05 was considered significant. The statistical analysis was carried out using Prism software (version 9.1.0; GraphPad Software, LLC).

Results

The mean HKA angle was 180 ± 2.57°, the LDFA was 86.1 ± 1.87°, the MPTA was 86.1 ± 2.15°, the PPTA was 84.6 ± 2.58°, the LPPTA was 84.9 ± 3.17°, the MPPTA was 85.1 ± 3.21°, the PDFA was 85.3 ± 1.50° and the nwJLCA was 0.82 ± 1.32° (Table 1).

There was a significant difference between males and females in the HKA, LDFA and MPPTA ($p < 0.001$). There was also a significant difference in the morphotype ($p < 0.001$) with a larger share of NA morphotypes in women, larger share of Var morphotype in men and larger share of Val morphotypes in women (Table 2). Within the three morphotypes, there was a significant difference in the nwJLCA ($p < 0.01$), LDFA, MPTA, PDFA and MPPTA angles ($p < 0.001$) (Table 3).

We found 45 different functional knee phenotypes in our study population, with 25 of them being found in both sexes. There was a significant difference in the functional knee phenotypes between men and women. The three most common phenotypes in men were $NEU_{HKA}0°$ + $NEU_{FMA}0°$ + $NEU_{TMA}0°$ (23.5%), $VAR_{HKA}3°$ + $NEU_{FMA}0°$ + $VAR_{TMA}3°$ (16.8%) and $NEU_{HKA}0°$ + $NEU_{FMA}0°$ + $VAR_{TMA}3°$ (7.5%).

The three most common phenotypes in women were $NEU_{HKA}0°$ + $NEU_{FMA}0°$ + $NEU_{TMA}0°$ (18%), $VAL_{HKA}3°$ + $VAL_{FMA}3°$ + $NEU_{TMA}0°$ (14.2%) and $NEU_{HKA}0°$ + $VAL_{FMA}3°$ + $VAR_{TMA}3°$ (10.8%) (Figure 2).

Discussion

This study determined the mean values for lower limb alignment in healthy Caucasian adults and found significant differences between men and women in the HKA and LDFA angles.

Our LDFA and MPTA values were lower than those by Paley et *al.* [19] and Bellemans et *al*. [20]. The inherent varus described in that study was not found [20]. There are two potential explanations. These two studies involved a radiographic analysis of the entire lower limb during weight bearing. If the knee is healthy, weightbearing causes adductor activation that can induced varus on the HKA values. In a population of arthritic patients, weight bearing will have an effect on HKA, correlated to wear. However, this effect appears to become significant especially during single-leg weight-bearing or if the osteoarthritis is advanced [21]. These scenarios do not correspond to our study population. A 2D analysis can have bias related to incorrect knee rotation or flexion when the images are made, which could also alter the angles [12-13,20,22-24].

A lower MPTA angle was found, which could be an additional argument against isolated corrections at the tibia, where there is a high risk of over-correction. When the planned MPTA is > 95° [25] the tilt of the joint line increases 4.9° postoperatively. A joint line greater than 4° is correlated to worse functional outcomes [26]. When it is less than 4°, the survival is 100% between 5 and 10 years [27]. To prevent this, it is recommended to carry out a double osteotomy to limit the joint line tilt [28-29].

Other than the MPPTA, we found no significant differences between sexes in the coronal plane. This evaluation is less clearly defined in the literature [30]. It plays a key role in the longevity of implants, range of motion and impacts the tension in the cruciate ligaments [22]. During proximal tibial osteotomy, the corrective procedure in the coronal plane also impacts the sagittal plane [9]. At the tibia, the values of the tibial slope are between 0 and 7° [22]. Paley et *al.* [19] found values of 9° ± 4° at the tibia and 6° ± 4° at the femur. This evaluation is difficult on conventional radiography, which is not very reproducible and varies depending on which anatomical reference axis is chosen [30]. Ho et *al.* [22] found values at the tibia of 11.2° ± 3° based on 3D reconstruction from CT images. The alignment of the lower limb is significantly different in the coronal and sagittal planes between different ethnic groups [15]. This can be explained by a specific lifestyle in some ethnic groups. For example, in an Asian population such as the one featured by Ho et *al.* [22], the lifestyle is closer to the ground (either kneeling or squatting) contributing to a prevalence of varus lower limb alignment [31].

The majority of morphotypes were neutral with association of tibial varus combined with femoral valgus, a larger share of varus morphotypes in men and conversely, valgus in women. Nevertheless, the most common phenotype was a combination of $NEU_{HKA}0°$ + $NEU_{FMA}0°$ + $NEU_{TMA}0°$ (20.5%), and in each sex. Men more often had a varus phenotype stemming from the tibia while women had a valgus phenotype stemming from the femur. Hirschmann et *al.* [13] found the “NEU” phenotypes the most, but with no valgus in women. This difference can be explained by a large population that had a more balanced sex ratio. In this same study [13], they also found that a small number of patients had a phenotype similar to mechanical alignment, corresponding to the NEU_{HKA} (180°) + VAR_{FMA}3° (90°) + VAL_{TMA}3° (90°) phenotype. The share was 2.6% for men and 2.2% for women in the study. It was 5.6% for men and 3.6% for women in the Hirschmann et *al.* study [13]. This is another reason to question this alignment goal during a total knee joint replacement. This objective is used to maximize implant longevity [32], although it was not found for a modern cemented total knee arthroplasty at 20 years' follow-up [33]. It remains that 20% of patients are not satisfied with the joint replacement [34] and more than half the patients have residual pain [35].

New alignment objectives have been proposed [36], which are closer to the initial anatomy and provide good short-term results [37]. Hirschmann et *al.* [13] found that restricted kinematic alignment appears to correspond to a larger share of phenotypes.

The current study has several limitations. It was done based on 3D reconstruction models that do not take into account lower limb alignment in a weight bearing stance. A comparison of our findings with a weight bearing analysis, such as the one provided by a stereo-radiographic imaging system, could be interesting. This was a retrospective analysis of a database. The analyzed patients were asymptomatic without knee osteoarthritis. They were at the hospital for other medical conditions. Hence, we have no knowledge of their habits, medical history or sports activities.

However, this study is specific to an ethnic group using a validated and reproducible reconstruction technique, which provides information on anatomical alignment in both the coronal and sagittal planes in a sizeable cohort.

We determined the mean values of lower limb alignment in healthy Caucasian patients and found a significant difference between men and women in the HKA, LDFA, MPPTA angles along with the morphotype and functional knee phenotype.

Conflict of interest: RS is a consultant for SERF. TV, EJ and PM have no conflict of interest to declare. SLA and AF are employees of Stryker. MO is a consultant for Stryker, Arthrex and Newclip.

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Author contributions:

Renaud Siboni: Writing of article, data analysis

Tristan Vialla: data analysis

Etienne Joseph: Critical review of the article

Sally LiArno: Data collection

Ahmad Faizan: Data collection

Pierre Martz: Critical review of the article

Matthieu Ollivier: Study sponsor, review and correction of article

Table 1: Results of the CT scan analysis

Variables	Mean (SD)	min	max	n
Age (years)	61.9 (14.8)	21.0	92.0	545
BMI (kg/m²)	25.6 (4.63)	15.8	41.9	478
Height (cm)	169 (8.42)	142	189	480
Mass (kg)	73.0 (14.6)	44.0	110	478
HKA angle (degrees)	180 (2.57)	171	187	586
LDFA (degrees)	86.1 (1.87)	80.1	91.0	586
MPTA (degrees)	86.1 (2.15)	77.7	92.3	586
PPTA (degrees)	84.6 (2.58)	77.0	94.5	586
LPPTA (degrees)	84.9 (3.17)	73.8	94.7	586
MPPTA (degrees)	85.1 (3.21)	76.2	94.8	586
PDFA (degrees)	85.3 (1.50)	80.8	88.9	586
nwJLCA (degrees)	0.82 (1.32)	–6.90	7.10	586

BMI: Body Mass Index; HKA: Hip Knee Ankle; LDFA: Lateral Distal Femoral Angle; MPTA: Medial Proximal Tibial Angle; PPTA: Posterior Proximal Tibial Angle; LPPTA: Lateral Posterior Proximal Tibial Angle; MPPTA: Medial Posterior Proximal Tibial Angle; PDFA: Posterior Distal Femoral Angle; nwJLCA: non weightbearing joint line convergence angle

Table 2: Outcomes by sex

Variables (Mean)	Women (n = 317)	Men (n = 269)	n	p
Age (years)	60.1 (±15.9)	64.0 (±13.2)	545	**<0.01**
BMI (kg/m²)	25.5 (±5.12)	25.8 (±3.92)	478	0.59
Height (cm)	165 (±7.23)	173 (±7.49)	480	**<0.001**
Weight (kg)	69.5 (±14.4)	77.5 (±13.7)	478	**<0.001**
HKA (degrees)	180.3 (±2.46)	179.0 (±2.52)	586	**<0.001**
LDFA (degrees)	85.6 (±1.90)	86.8 (±1.61)	586	**<0.001**
MPTA (degrees)	86.3 (±2.14)	86.0 (±2.16)	586	0.14
PPTA (degrees)	84.5 (±2.50)	84.6 (±2.67)	586	0.43
LPPTA (degrees)	85.1 (±2.99)	84.7 (±3.36)	586	0.086
MPPTA (degrees)	84.7 (±3.06)	85.6 (±3.31)	586	**<0.001**
PDFA (degrees)	85.3 (±1.59)	85.2 (±1.39)	586	0.34
nwJLCA (degrees)	0.74 (±1.43)	0.92 (±1.17)	586	0.081
Morphotype NA	246 (78%)	196 (73%)	442	**<0.001**
Var	24 (7.6%)	55 (20%)	79	-
Val	47 (15%)	18 (6.7%)	65	-

BMI: Body Mass Index; HKA: Hip Knee Ankle; LDFA: Lateral Distal Femoral Angle; MPTA: Medial Proximal Tibial Angle; PPTA: Posterior Proximal Tibial Angle; LPPTA: Lateral Posterior Proximal Tibial Angle; MPPTA: Medial Posterior Proximal Tibial Angle; PDFA: Posterior Distal Femoral Angle; nwJLCA: non weightbearing joint line convergence angle; NA: Neutral Alignment; Var: Varus; Val: Valgus

Table 3: Results by morphotype

Variables	Neutral (n = 442)	Varus (n = 79)	Valgus (n = 65)	n	p
HKA (degrees)	180 (±1.59)	176 (±1.29)	184 (±0.77)	586	**<0.001**
LDFA (degrees)	86.1 (±1.69)	87.7 (±1.79)	84.6 (±1.69)	586	**<0.001**
MPTA (degrees)	86.2 (±1.79)	83.9 (±2.07)	88.6 (±1.64)	586	**<0.001**
PPTA (degrees)	84.6 (±2.44)	84.1 (±3.26)	85.0 (±2.50)	586	0.094
LPPTA (degrees)	85.0 (±3.09)	85.2 (±3.67)	84.5 (±3.08)	586	0.41
MPPTA (degrees)	85.1 (±3.00)	83.9 (±3.90)	86.4 (±3.11)	586	**<0.001**
PDFA (degrees)	85.3 (±1.44)	84.3 (±1.59)	86.0 (±1.27)	586	**<0.001**
nwJLCA (degrees)	1.08 (±0.969)	1.27 (±1.17)	-1.48 (±1.27)	586	**<0.01**
Sex Female	246 (56%)	24 (30%)	47 (72%)	317	**<0.001**
Male	196 (44%)	55 (70%)	18 (28%)	269	

HKA: Hip Knee Ankle; LDFA: Lateral Distal Femoral Angle; MPTA: Medial Proximal Tibial Angle; PPTA: Posterior Proximal Tibial Angle; LPPTA: Lateral Posterior Proximal Tibial Angle; MPPTA: Medial Posterior Proximal Tibial Angle; PDFA: Posterior Distal Femoral Angle; nwJLCA: non weightbearing joint line convergence angle

Figure 1: Diagram showing the angles measured for this study
LDFA: Lateral Distal Femoral Angle; MPTA: Medial Proximal Tibial Angle; PPTA: Posterior Proximal Tibial Angle; PDFA: Posterior Distal Femoral Angle; nwJLCA: non weightbearing joint line convergence angle

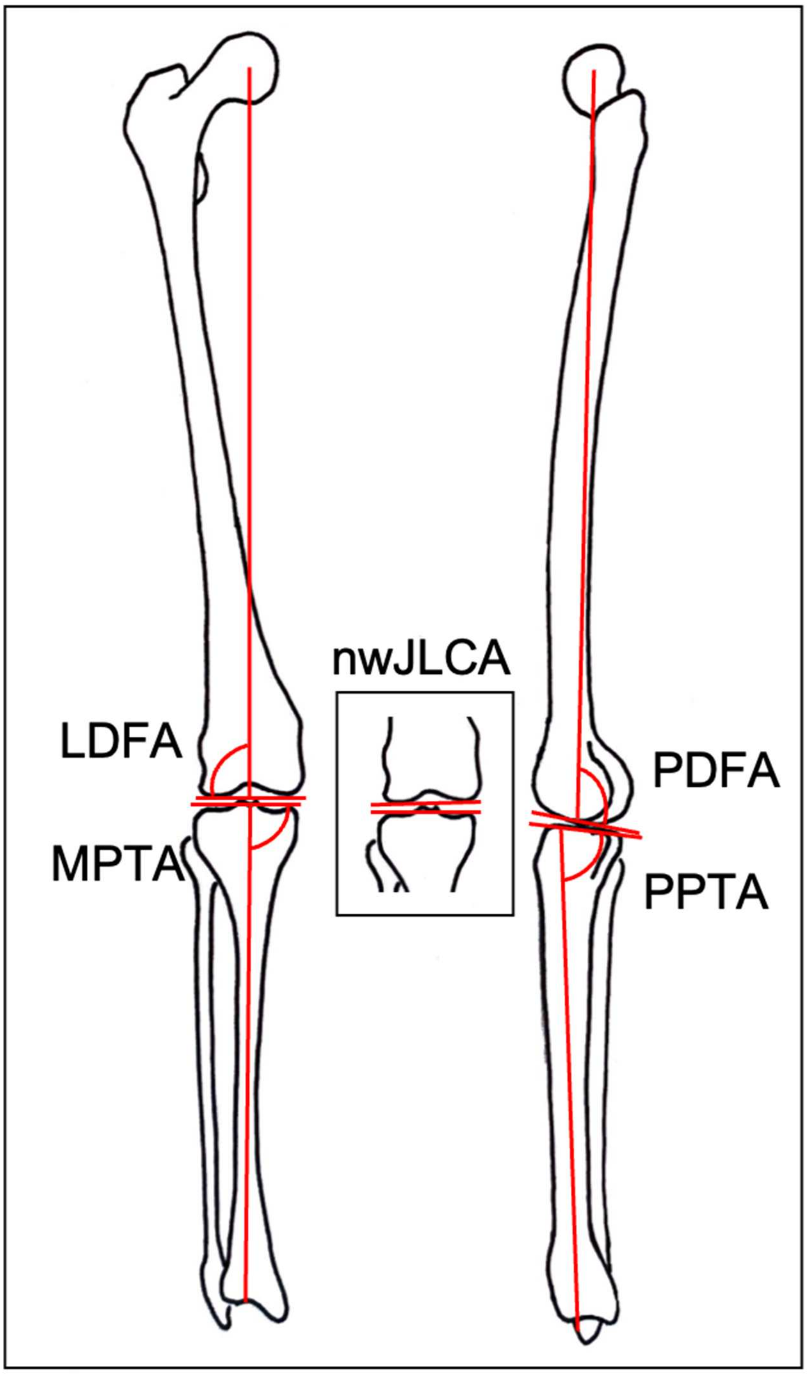
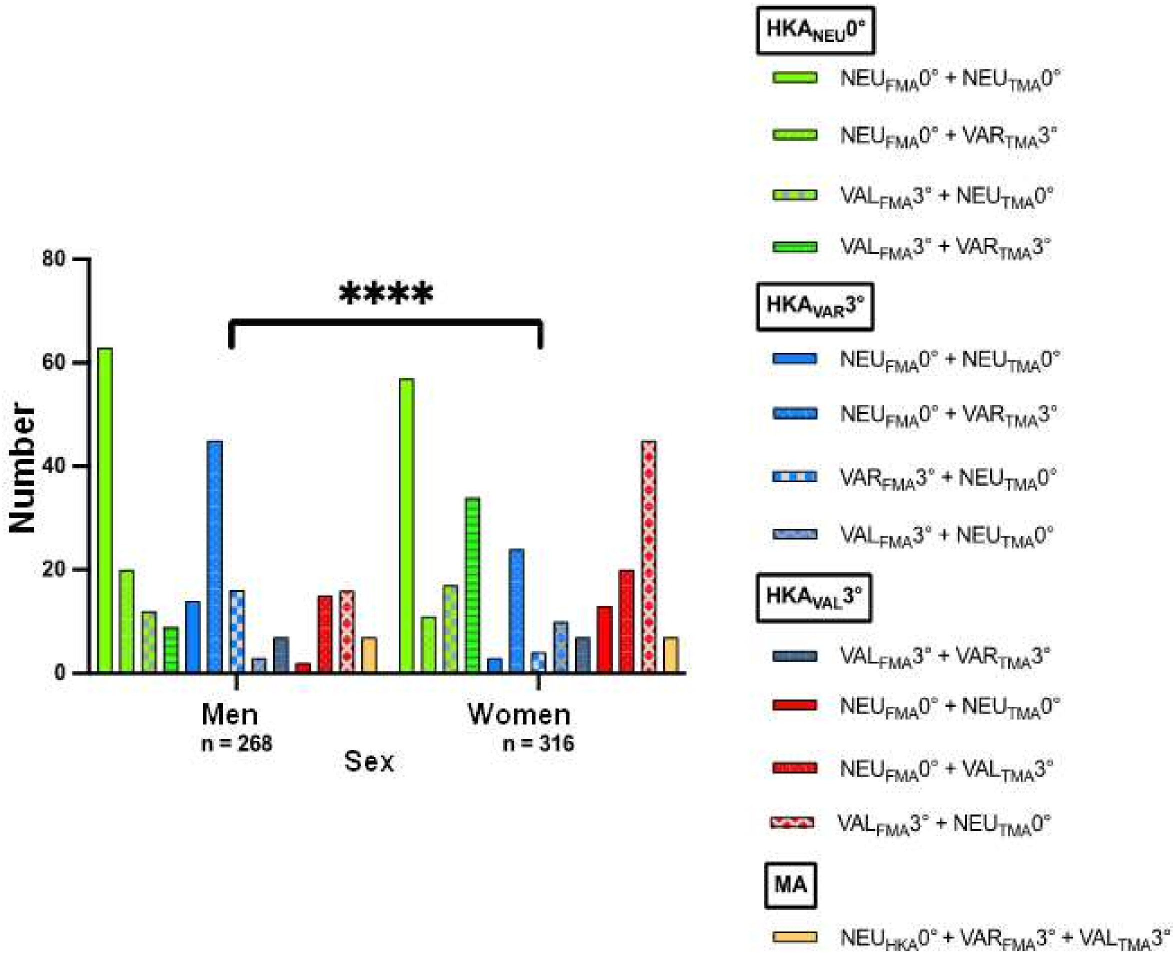


Figure 2: The main functional knee phenotypes as defined by Hirschmann et *al.* [13] by sex



HKA: hip-knee-ankle; NEU: Neutral; Var: Varus; Val: Valgus; n (number); ****: $p < 0.0001$; MA: mechanical alignment

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