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The Chitranjan Ranawat Award

Is Neutral Mechanical Alignment Normal for All Patients?

The Concept of Constitutional Varus

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Abstract

Background Most knee surgeons have believed during TKA neutral mechanical alignment should be restored. A number of patients may exist, however, for whom neutral mechanical alignment is abnormal. Patients with so-called "constitutional varus" knees have had varus alignment since they reached skeletal maturity. Restoring neutral alignment in these cases may in fact be abnormal and undesirable and would likely require some degree of medial soft tissue release to achieve neutral alignment.

Questions/purposes We investigated what percentage of the normal population has constitutional varus knees and what are the contributing factors.

Subjects and Methods We recruited a cohort of 250 asymptomatic adult volunteers between 20 and 27 years old for this cross-sectional study. All volunteers had full-leg standing digital radiographs on which 19 alignment parameters were analyzed. The incidence of constitutional varus alignment was determined and contributing factors were analyzed using multivariate prediction models.

Results Thirty-two percent of men and 17% of women had constitutional varus knees with a natural mechanical alignment of 3° varus or more. Constitutional varus was associated with increased sports activity during growth, increased femoral varus bowing, an increased varus femoral neck-shaft angle, and an increased femoral anatomic mechanical angle.

Conclusions An important fraction of the normal population has a natural alignment at the end of growth of 3° varus or more. This might be a consequence of Hueter-Volkmann's law. Restoration of mechanical alignment to neutral in these cases may not be desirable and would be unnatural for them.

Level of Evidence Level I, diagnostic study. See Guidelines for Authors for a complete description of levels of evidence.

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Each author certifies that his or her institution has approved the human protocol for this investigation and that all investigations were conducted in conformity with ethical principles of research.

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Introduction

The main purpose of either partial or total knee arthroplasty is to replace the eroded cartilage and bone with an artificial implant that compensates for the erosion or damage. When doing so, restoration of neutral mechanical alignment is traditionally considered an important factor with respect to the durability of the implant [1, 4, 15, 19, 22, 24, 30, 31, 34]. When neutral mechanical alignment is restored, the mechanical axis of the leg passes through the center of the knee, which leads to an even mediolateral load distribution and a minimized risk for implant wear and component loosening [1, 2, 4, 5, 15, 24, 31, 37]. For this reason, several techniques to obtain intraoperative restoration of mechanical alignment have been used in the past, usually by referencing of intramedullary or extramedullary alignment rods or using more sophisticated computerized navigation methods [6, 23, 25, 30, 39].

Recently, however, the concept of anatomic restoration has gained interest among knee surgeons [16, 17, 34]. Given this philosophy, the natural anatomy of the knee is restored by using patient-specific implants that selectively or completely resurface the eroded or damaged parts of the knee back to its original anatomic contours. This approach would not necessarily restore the alignment to neutral but rather to the natural alignment of the knee before the disease or damage occurred. Indeed, a number of patients may exist for whom neutral mechanical alignment is abnormal. Patients with so-called "constitutional varus" knees have had varus alignment since the end of their growth. Restoring neutral alignment in these cases would be abnormal for them and in fact would almost per definition require some degree of medial soft tissue release (Fig. 1).

At the same time, anatomic restoration of these knees would lead to a mechanical alignment in varus, which could jeopardize the long-term survivorship of the procedure. The surgeon is therefore confronted with a strategic dilemma in these patients with constitutional varus: to opt for either neutral mechanical alignment restoration while realizing that this is abnormal for that specific patient or anatomic restoration and accepting varus mechanical alignment. However, there are no data documenting whether constitutional varus exists in the normal population, and if so, in what percentage of healthy individuals it occurs. Also, it is unclear how these patients could be recognized during surgery.

We therefore determined the percentage of the normal population having constitutional varus knees and the factors contributing to constitutional varus.

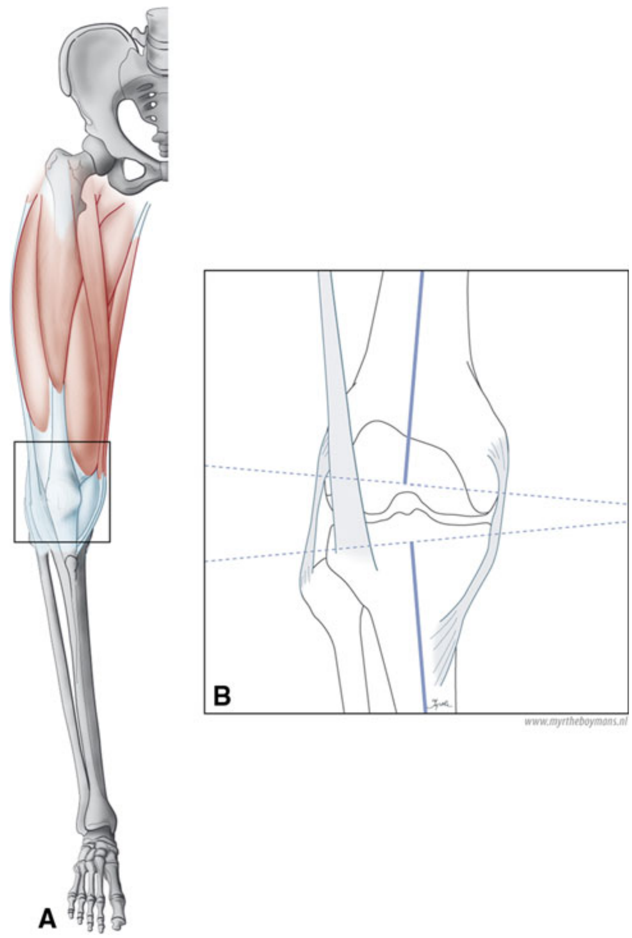

Fig. 1A–B (**A**) A diagram depicts a knee with constitutional varus and without arthritic changes. (**B**) Restoration of neutral mechanical alignment during TKA might be abnormal or undesirable for such a knee and would almost per definition require some degree of medial soft tissue release.

Subjects and Methods

We recruited 250 young healthy adults aged between 20 and 27 years for this cross-sectional prevalence study. Only healthy volunteers with no orthopaedic or trauma history were allowed to participate. We excluded subjects who had been treated or seen for a musculoskeletal condition or trauma and/or seen by a specialist. All study participants were recruited as volunteers at movie theaters, technical high school and university campuses, or job recruitment bureaus during the period between October 2009 and March 2010. We included 125 male and 125 female volunteers. All volunteers consented to participate in the study, which was approved by the ethical commission of our institution before the first inclusion. Study participation was cost-free for the participants, and all participants received two free movie tickets as thanks for their participation.

All volunteers underwent full-leg standing digital radiography on which 19 different alignment parameters were analyzed. The weightbearing full-leg radiographs were obtained as described by Paley [28] with the subjects standing barefoot and the feet together in the "stand at attention" position while the patellae were oriented forward. The xray beam was centered on the knee with the radiography tube at a distance of 305 cm. Three 350- × 430-mm cassettes were placed immediately behind the subject and the AGFA MIMOSA VIPS 1.3.00 software package (Agfa-Gevaert, Mortsel, Belgium) was used for digital stitching. A setting of 500 mA and a kilovoltage of 75 kV were used as the standard and individually adapted when necessary. The whole pelvis was included in the radiographs and the gonads were always shielded. All radiographs were calibrated and all measurements were performed by the same person (WC) using the AGFA PACS software package (Agfa-Gevaert) and previously described methodology [3, 13, 22, 26, 28, 36, 38].

For measurements of the joint centers and axes, the center of the femoral head was determined using a digital template with concentric circles. The center of the knee was determined as the intersection of the midline between the tibial spines and the midline between the femoral condyles and tip of the tibiae. The center of the ankle was determined as the midwidth of the talus. The mechanical femoral axis was defined as the line from the center of the femoral head to the center of the knee. The line from the center of the knee to the center of the ankle was defined as the mechanical tibial axis. The anatomic axis of the proximal femur was determined as the line from the midpoint of cortical width at the proximal ⅓ femoral length to the midpoint of cortical width at the level of the lesser trochanter. The anatomic axis of the femur was defined as the line from the center of the knee to the intersection of the bisector of the femoral neck and the anatomic axis of the proximal femur, which was defined as the proximal reference point. The distal reference point was defined as the point midway the shaft between the midpoint of cortical width 10 cm proximal to the knee and the midpoint of cortical width at the lesser trochanter. The distal femoral axis of the femur was defined as the line from the center of the knee to this distal reference point.

For length measurements, the distance from the center of the femoral head to the center of the knee was defined as the femoral length. The total limb length was defined as the distance between the center of the femoral head to the center of the ankle. The distance between the mechanical axis line and the center of the knee was called the mechanical axis deviation (MAD). Medial and lateral MADs were referred to as varus or valgus alignment, respectively. The bisector of the femoral neck was defined as the line from the center of the femoral head to the midpoint of the femoral neck base. The distance from the center of the femoral head to the proximal reference point was defined as the neck-shaft length (NSL). The pelvic width was defined as the distance between the two anterosuperior iliac spines. The morphotype of the patient was determined as the ratio between pelvic width and total limb length.

One of us (WC) made all radiographic measurements. Previous literature has demonstrated high intra- and interobserver reliability using this methodology [8, 32]. The hip-knee-ankle (HKA) angle was defined as the angle formed by the mechanical femoral axis and the mechanical tibial axis. The HKA angle was expressed as a deviation from 180° with a negative value for varus and positive value for valgus alignment.

The lateral angle formed between the mechanical femoral axis and the knee joint line of the distal femur was defined as the mechanical lateral distal femoral angle (mLDFA). The medial proximal tibial angle (MPTA) was defined as the medial angle formed between the mechanical tibial axis and the knee joint line of the proximal tibia. The angle between the knee joint lines of the distal femur and proximal tibia was called the joint line convergence angle (JLCA). The angle formed by the anatomic axis of the femur and the bisector of the femoral neck was called the medial neck-shaft angle (MNSA). The knee valgus proximal angle (KVPA) was determined as the angle determined by the mechanical axis of the femur and the anatomic axis of the femur. The angle between the line from the midpoint of cortical width at the lesser trochanter to the distal reference point and the line from the distal reference point to the midpoint of cortical width 10 cm proximal to the knee was defined as the femoral bow. The lateral proximal femoral angle (LPFA) was defined as the angle between the line connecting the tip of the greater trochanter with the center of the femoral head and the mechanical femoral axis.

In addition to the radiographic analysis, all patients were asked to provide information on their physical and sports activity level during their second decade of life. Based on this questionnaire, patients were categorized into three groups. Patients without physical activity (beyond those obliged at school) were allocated in Group 1, patients who had performed impact sports averaging between 1 and 3 hours per week in Group 2, and patients who had performed impact sports more than 3 hours per week in Group 3.

Knees were considered as having constitutional varus if the HKA angle was −3° or less, as normal if the HKA angle was between −3° and +3°, and as having constitutional valgus if the HKA angle was 3° or more. A subject was considered to have an alignment in varus (or valgus) when at least one of the legs had alignment in varus (or valgus). Percentages and 95% confidence intervals were calculated for constitutional varus, constitutional valgus, and normal alignment. Multivariable linear mixed models with random subject effects and Tukey adjustments were used to analyze contributing factors to the HKA angle (angle measurements, length measurements, and subject characteristics). An R^2 was calculated based on the linear regression between the predicted values and the observed data. P values smaller than 5% were considered significant. We used SAS® Version 9.2 (SAS Institute, Inc, Cary, NC) for all analyses.

Results

Eighty (32%) of the male knees and 43 (17.2%) of the female knees had constitutional varus alignment with an

HKA angle of −3° or less (Table 1) (Fig. 2). The average HKA angle was smaller ($p < 0.001$) in male than female knees: −1.9° (SD, 2.1°) versus −0.8° (SD, 2.4°), respectively. One hundred sixty-five (66%) of the male knees (Fig. 3) and 200 (80%) of the female knees (Fig. 4) had an HKA angle of between −3° and +3°. Five (2%) of the male and seven (2.8%) of the female knees had an HKA angle of ≥ +3°.

When controlled for sex and interaction, the greatest ($R^2 = 0.408$, $p < 0.001$) contributor to constitutional varus was the MPTA (Table 2). Other contributors were mLDFA ($R^2 = 0.294$), KVPA ($R^2 = 0.077$), MNSA ($R^2 = 0.060$), femoral bowing ($R^2 = 0.063$), and increased physical activity level during the second decade of life ($R^2 = 0.081$).

The average HKA angle was smaller in the subjects with increased sports activity level during their second decade of life (Group 3) compared to the subjects from Group 1 ($p < 0.01$): −2.3° (SD, 2.6°) versus −0.9° (SD, 2.2°); and compared to the subjects from Group 2 ($p < 0.05$), who had an average HKA angle of −1.3° (SD, 2.3°).

Table 1. Measurement parameters all knees together and for both genders separately

Parameter	All (n = 500)	Men (n = 250)	Women (n = 250)	p Value (between genders)
HKA angle (°)	−1.33 ± 2.34	−1.87 ± 2.42	−0.79 ± 2.13	< 0.0001
mLDFA (°)	87.90 ± 1.74	87.88 ± 1.70	87.92 ± 1.78	0.8381
MPTA (°)	87.04 ± 2.07	86.50 ± 2.17	87.58 ± 1.82	< 0.0001
JLCA (°)	−0.51 ± 1.05	−0.47 ± 0.98	−0.56 ± 1.12	0.4406
KVPA (°)	4.45 ± 0.58	4.52 ± 0.62	4.38 ± 0.51	0.0403
MNSA (°)	134.95 ± 5.18	134.27 ± 5.36	135.63 ± 4.91	0.0262
LPFA (°)	86.58 ± 4.77	87.17 ± 4.95	85.99 ± 4.51	0.0394
Femoral bowing (°)	0.20 ± 1.77	0.38 ± 1.80	0.02 ± 1.73	0.0811
MAD (mm)	−4.83 ± 8.58	−6.94 ± 9.24	−2.72 ± 7.30	< 0.0001
Femur length (mm)	469.15 ± 30.59	487.45 ± 25.66	450.84 ± 23.33	< 0.0001
Total leg length (mm)	859.57 ± 57.50	894.79 ± 48.59	824.35 ± 42.12	< 0.0001
Neck-shaft length (mm)	52.20 ± 4.80	54.31 ± 4.65	50.09 ± 3.96	< 0.0001
Height (m)	1.75 ± 0.09	1.82 ± 0.07	1.69 ± 0.06	< 0.0001
Weight (kg)	68 ± 12.29	75.38 ± 10.30	61.35 ± 9.91	< 0.0001
BMI	22 ± 2.94	22.71 ± 2.48	21.49 ± 3.24	0.00100
Morphotype	0.33 ± 0.03	0.32 ± 0.02	0.34 ± 0.04	< 0.0001

Values are expressed as mean ± SD; HKA angle = hip-knee-ankle angle; mLDFA = mechanical lateral distal femoral angle; MPTA = medial proximal tibial angle; JLCA = joint line convergence angle; KVPA = knee valgus proximal angle; MNSA = medial neck-shaft angle; LPFA = lateral proximal femoral angle; MAD = mechanical axis deviation; BMI = body mass index.

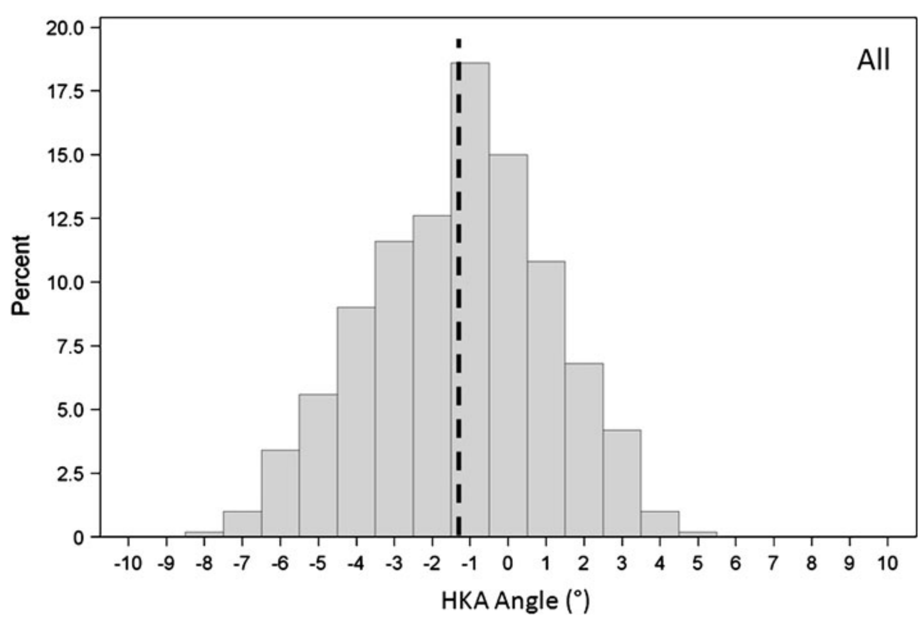

Fig. 2 A histogram for HKA angle depicts the distribution and mean (1.3° varus; dotted line) of all 500 knees. HKA = hip-knee-ankle.

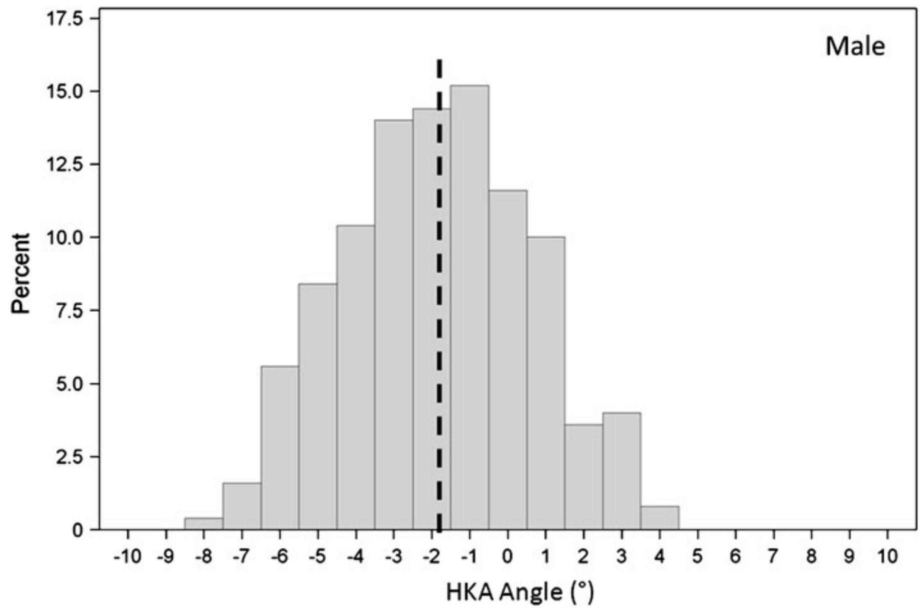

Fig. 3 A histogram for HKA angle depicts the distribution and mean (1.9° varus; dotted line) of male knees. HKA = hip-knee-ankle.

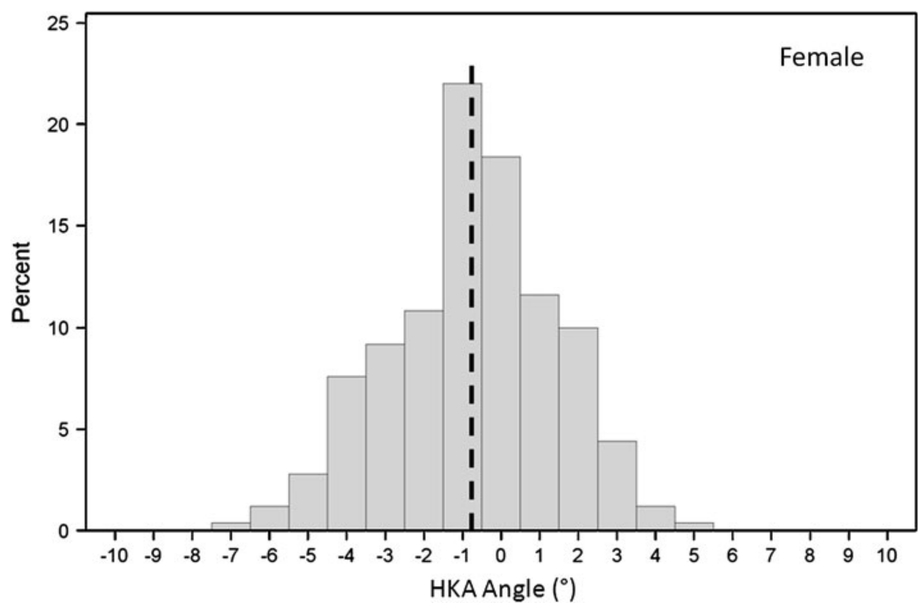

Fig. 4 A histogram for HKA angle depicts the distribution and mean (0.8° varus; dotted line) of female knees. HKA = hip-knee-ankle.

Body mass index; morphotype, height, and weight of the patient; length measurements; JLCA; and LPFA had no contribution to the development of constitutional varus.

Discussion

Restoration of neutral mechanical alignment is considered a cornerstone for successful and durable knee arthroplasty [1, 4, 15, 20, 23, 24, 30, 31, 34]. The reason for this general belief is that neutral mechanical alignment is considered by most surgeons as the normal healthy situation, which leads to symmetric mediolateral joint loading, and that therefore neutral mechanical restoration should be attempted to provide a durable and successful arthroplasty [1, 2, 4, 5, 15, 24, 32, 37]. Whether this is correct can be questioned, however. Having been in orthopaedic practice for many years, we believe a certain fraction of the normal population does not have neutral alignment at the end of skeletal growth but rather some degree of varus. If this is correct, restoring the alignment to neutral at a later stage in the life of these patients, for example at the time of knee arthroplasty, would be abnormal and in fact unnatural for them, since it would implicate an overcorrection toward their natural situation in which they had spent their life since skeletal maturity. In this study, we asked whether

Table 2. Measurement parameters for constitutional varus knees in comparison to neutral and valgus knees

Parameter	All (n = 500)			Men (n = 250)			Women (n = 250)		
	Varus (HKA ≤ − 3°)	Neutral (HKA ± 3°)	Valgus (HKA ≥ + 3°)	Varus (HKA ≤ − 3°)	Neutral (HKA ± 3°)	Valgus (HKA ≥ + 3°)	Varus (HKA ≤ − 3°)	Neutral (HKA ± 3°)	Valgus (HKA ≥ + 3°)
HKA angle (°)	−4.45 ± 1.06§	−0.46 ± 1.50‡	3.56 ± 0.63$^{\|}$	−4.46 ± 1.1§	−0.74 ± 1.5‡	3.43 ± 0.4$^{\|}$	−4.12 ± 0.94§	−0.23 ± 1.44‡	3.67 ± 0.8$^{\|}$
mLDFA (°)	89.03 ± 1.46§	87.61 ± 1.6‡	85.45 ± 1.89†	88.9 ± 1.48§	87.5 ± 1.5‡	85.6 ± 1.8†	89.2 ± 1.54§	87.7 ± 1.66‡	85.37 ± 2.1†
MPTA (°)	85.13 ± 1.81§	87.6 ± 1.74‡	89.06 ± 1.42†	84.68 ± 1.77§	87.3 ± 1.76‡	89.5 ± 1†	85.96 ± 1.6*	87.89 ± 1.67‡	88.67 ± 1.68
JLCA (°)	−0.44 ± 1.11	−0.53 ± 1.04	−0.64 ± 0.85	−0.31 ± 1.1	−0.54 ± 0.92	−0.53 ± 0.76	−0.67 ± 1.1	−0.53 ± 1.13	−0.73 ± 0.98
KVPA (°)	4.51 ± 0.62*	4.44 ± 0.55	3.98 ± 0.67	4.6 ± 0.67	4.5 ± 0.59	4.25 ± 0.93	−4.35 ± 0.49	4.4 ± 0.51	3.76 ± 0.21$^{\|}$
MNSA (°)	134.7 ± 5.56	134.94 ± 4.99	137.52 ± 6.51	133.9 ± 5.9	134.4 ± 5.0	133.7 ± 7.55	136.1 ± 4.6	135.4 ± 4.9	140.8 ± 3.16
LPFA (°)	86.37 ± 5.04	86.71 ± 4.63	85.0 ± 5.84	86.9 ± 5.6	87.3 ± 4.65	88.5 ± 4.62	85.4 ± 3.67	86.3 ± 4.58	82.0 ± 5.27
Femoral bowing (°)	0.45 ± 1.69	0.11 ± 1.80	0.16 ± 1.62	0.6 ± 1.64	0.3 ± 1.88	−0.05 ± 1.45	0.2 ± 1.75	−0.03 ± 1.74	0.34 ± 1.84
MAD (mm)	−16.16 ± 4.47§	−1.7 ± 5.40‡	13.58 ± 2.87$^{\|}$	−16.1 ± 7.95	−2.7 ± 5.76	7.5 ± 13.06	−14 ± 3.22	−0.9 ± 4.93	13.7 ± 3.28
Femur length (mm)	466.1 ± 31.16	469.46 ± 29.8	489.3 ± 40.84	482.8 ± 22.9	488.7 ± 25.1	513.5 ± 50.6	435.3 ± 18	453.6 ± 23.2	467.1 ± 10.8
Total leg length (mm)	853.2 ± 58.2	860.49 ± 56.2	893.69 ± 75.75	883.9 ± 43.5	898.3 ± 47.7	940.7 ± 92.3	796.7 ± 35	827.9 ± 48.3	850.8 ± 16.5
Neck-shaft length (mm)	52.35 ± 5.03	52.19 ± 4.73	51.2 ± 4.90	54.4 ± 4.66	54.3 ± 4.65	53.1 ± 5.24	48.5 ± 3.07	50.4 ± 4.05	49.3 ± 4.64
Height (m)	1.76 ± 0.09	1.75 ± 0.09	1.8 ± 0.1	1.8 ± 0.06	1.8 ± 0.07	1.9 ± 0.1	1.7 ± 0.06	1.7 ± 0.06	1.7 ± 0.04
Weight (kg)	68.17 ± 11.77	68.2 ± 12.33	72.18 ± 15.9	74.4 ± 6.84	76 ± 11.5	68 ± 16.9	56.9 ± 9.72	62.5 ± 9.83	62.7 ± 3.06
BMI	21.91 ± 2.52	22.2 ± 3.17	21.97 ± 2.67	22.5 ± 2.01	22.8 ± 2.67	23.4 ± 2.77	20.7 ± 2.48	21.7 ± 3.39	20.2 ± 0.92

Values are expressed as mean ± SD; *significant difference between varus and valgus ($p < 0.05$); †significant difference between valgus and neutral ($p < 0.05$); ‡significant difference between varus and neutral ($p < 0.001$); §significant difference between varus and valgus ($p < 0.001$); $^{\|}$significant difference between valgus and neutral ($p < 0.001$); HKA angle = hip-knee-ankle angle; mLDFA = mechanical lateral distal femoral angle; MPTA = medial proximal tibial angle; JLCA = joint line convergence angle; KVPA = knee valgus proximal angle; MNSA = medial neck-shaft angle; LPFA = lateral proximal femoral angle; MAD = mechanical axis deviation; BMI = body mass index.

constitutional varus really exists in the normal population and, if so, in what percentage of healthy individuals it occurs. Also, we aimed at discriminating factors that contribute to constitutional varus. This would allow recognition of the original type of deformity at the time of surgery.

Our study had a number of limitations. A single observer performed all the measurements; obviously the measurements may be influenced by the accuracy of the investigator and systematic bias can be introduced. However, a single observer assures consistency. The second limitation to our study is the use of full-leg standing radiographs for our measurements. Although this method is well validated in the literature and has excellent intra- and interobserver reliability, the rotational position of the lower extremities might influence the outcome of the measurements [8, 12, 13, 21, 27, 38]. The rotational position of the knee compared to the hip and ankle is variable, and a perceived constitutional varus could therefore in fact be an external rotation of one subject's limb as compared to another. In our study, however, the rotational position of the lower extremities was controlled by positioning the extremities with the patellae facing forward, as was used by many previous authors who have studied lower leg alignment [7, 18, 21, 22, 26, 28, 38]. We believe, by doing so, the rotational effect is minimized. An alternative could have been to use a Questor® precision radiograph frame (PARTEQ Innovations, Kingston, Canada), which however is unpractical and not frequently used in daily clinical practice [10–13]. Another option might have been to use CT scans, which could prevent potential mistakes in rotational position [34]. A disadvantage is however the higher radiation exposure, and therefore this method could ethically not be used in our large group of young healthy volunteers. Furthermore, we wanted to study standing alignment in the same way as is done in current clinical practice, which is with standard full-leg radiographs.

Our data show a substantial fraction of the normal population (32% of men, 17% of women) having a natural alignment at the end of growth of 3° varus or more. We have defined this as constitutional varus. These numbers may at first sight seem relatively high. Indeed, this finding has not been recognized so far, despite several published papers on normal lower leg alignment. This could be explained by a limited number of participants, a large variability in the subjects' age, recruitment in a hospital setting, lack of stratification, and selection bias of the subjects in these prior studies [7, 10, 11, 18, 22, 26–28, 36].

We also found the most important contributors to constitutional varus were the MPTA and the mLDFA, contributing 40.8% and 29.4%, respectively. Constitutional varus was also associated with increased femoral varus bowing, an increased varus femoral neck-shaft angle, and an increased femoral anatomic mechanical angle, confirming previous published work by Victor et al. [39]. These factors, which are detectable on a full-leg radiograph, could therefore serve to identify the patient with constitutional varus at the time of TKA, regardless of the osteoarthritic degeneration of the knee.

Also, constitutional varus was associated with increased sports activity in the second decade of life. The association of varus alignment with increased physical activity during growth has been raised by other authors before. Witvrouw et al. [42] have noted intense sports activity during growth leads to the development of varus knees, and this phenomenon occurs especially toward the end of the growth spurt. We believe such could be the consequence of Hueter-Volkmann's law, which states growth at the physes is retarded by increased compression, whereas reduced loading accelerates growth [14, 19, 33, 35, 40, 41]. The increased loads caused by the adduction moment on the knee during ambulation and physical activity could therefore lead to the development of varus alignment secondary to delayed growth on the medial side and accelerated growth on the lateral physes [14, 18, 42]. Cook et al. [9] alluded to this theory in a biomechanical study on the etiology of pediatric tibia vara.

Our findings should be interpreted cautiously, since this is an observational study on healthy patients and includes no correlation with osteoarthritic patients or patients who have had a TKA. The importance of neutral mechanical with respect to a durable and successful result after TKA does not disappear if a patient has constitutional varus. The questions that remain are however (1) whether there is a clinically important functional disadvantage of restoring knees with constitutional varus to neutral alignment after TKA, and conversely (2) whether there is a substantial mechanical disadvantage to leaving these knees in slight varus. Until these questions become solved, the debate continues on how alignment in these knees should be corrected at the time of TKA.

In view of this, a recent study by Parratte et al. [29] on 398 modern TKAs demonstrated no difference in survival at 15 years' followup for knees aligned within neutral ± 3° versus outliers, which made the authors suggest patient-specific dynamic aspects of gait and in vivo loading play a role such that, for every individual patient, there could be a specific ideal target value for postoperative alignment, which does not necessarily lie within 0° ± 3°. However, further research on this matter is necessary to support this hypothesis.

In summary, our data show a large fraction of the normal population (32% of men, 17% of women) has varus alignment once they have reached skeletal maturity. Our data therefore contribute to the existing studies on normal human lower leg alignment that have been published in the past and have uniformly reported the average normal leg alignment is not zero but in fact slightly greater than 1° mechanical varus and with a relatively large SD.

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