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Arithmetic hip-knee-ankle angle (aHKA): An algorithm for estimating constitutional lower limb alignment in the arthritic patient population

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Aims

Once knee arthritis and deformity have occurred, it is currently not known how to determine a patient's constitutional (pre-arthritic) limb alignment. The purpose of this study was to describe and validate the arithmetic hip-knee-ankle (aHKA) algorithm as a straightforward method for preoperative planning and intraoperative restoration of the constitutional limb alignment in total knee arthroplasty (TKA).

Methods

A comparative cross-sectional, radiological study was undertaken of 500 normal knees and 500 arthritic knees undergoing TKA. By definition, the aHKA algorithm subtracts the lateral distal femoral angle (LDFA) from the medial proximal tibial angle (MPTA). The mechanical HKA (mHKA) of the normal group was compared to the mHKA of the arthritic group to examine the difference, specifically related to deformity in the latter. The mHKA and aHKA were then compared in the normal group to assess for differences related to joint line convergence. Lastly, the aHKA of both the normal and arthritic groups were compared to test the hypothesis that the aHKA can estimate the constitutional alignment of the limb by sharing a similar centrality and distribution with the normal population.

Results

There was a significant difference in means and distributions of the mHKA of the normal group compared to the arthritic group (mean -1.33° (SD 2.34°) vs mean -2.88° (SD 7.39°) respectively; $p < 0.001$). However, there was no significant difference between normal and arthritic groups using the aHKA (mean -0.87° (SD 2.54°) vs mean -0.77° (SD 2.84°) respectively; $p = 0.550$). There was no significant difference in the MPTA and LDFA between the normal and arthritic groups.

Conclusion

The arithmetic HKA effectively estimated the constitutional alignment of the lower limb after the onset of arthritis in this cross-sectional population-based analysis. This finding is of significant importance to surgeons aiming to restore the constitutional alignment of the lower limb during TKA.

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Introduction

The distribution of lower limb alignment in the normal population is notably different to that seen in patients who require total knee arthroplasty (TKA).^{1–5} Progressive, asymmetric joint space narrowing during the disease process leads to exaggeration of the mechanical hip-knee-ankle (mHKA) angle

beyond changes due to bony deformity alone.⁶

With the rising interest in kinematic techniques in TKA, which aim to restore constitutional (pre-arthritic) alignment,^{7–16} an accurate and straightforward algorithm to estimate this measurement is required.¹⁷ However, to date, there has been no

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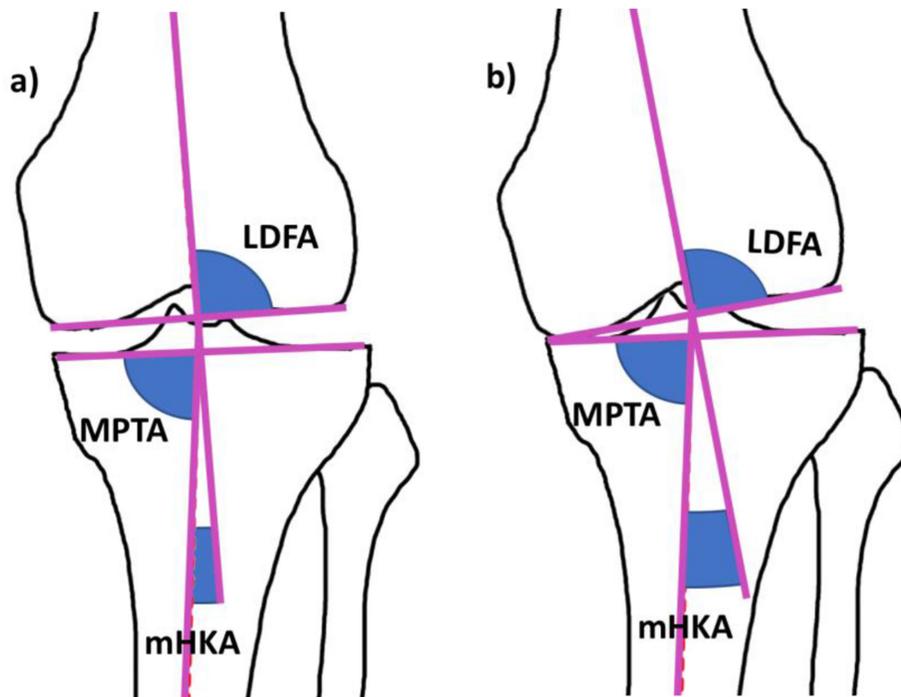


Fig. 1

Changes in coronal alignment and mechanical hip-knee-ankle angle (mHKA) in degenerative arthritis. a) Lateral distal femoral angle (LDFA), medial proximal tibial angle (MPTA) and mHKA in a knee with preserved joint space and mild constitutional varus alignment. b) The same knee following degenerative loss of medial joint space, showing a change in mHKA and no change to LDFA and MPTA.

validated method that can approximate what the constitutional alignment was prior to onset of deformity. Many patient-specific mapping systems use unvalidated proprietary algorithms, the details of which are often not clear to the surgeon, and most require costly 3D imaging that is otherwise not clinically indicated.^{8,9,15,16}

We propose using the user-friendly arithmetic HKA (aHKA) algorithm to estimate the pre-arthritic constitutional alignment of the lower limb using long leg radiographs.¹⁸ We aimed to validate this application of the algorithm by comparing normal-population alignment data with data from a sample population of patients with established arthritis. The purpose of this study was to determine if the aHKA is a reliable technique for estimating the constitutional alignment of the lower limb when degenerative arthritis is present. The primary hypothesis was that while the mHKA values between normal and arthritic groups would be significantly different, aHKA measurements would be similar between the groups, thereby validly approximating constitutional alignment.

Methods

We undertook a retrospective radiological, cross-sectional study comparing the aHKA in a normal population sample to the aHKA in a sample of arthritic patients requiring TKA. Ethics approval was conferred by Hunter

New England Local Health District (approval number EX201905-02).

Study groups. The normal population comprised 250 adults aged between 20 and 27 years from a previous cross-sectional prevalence study by one of the authors (JB).¹ Participants were recruited from Belgian high school and university campuses, movie theatres, and job recruitment bureaus between October 2009 and March 2010. In all, 250 of the volunteers (50%) were female. Only healthy volunteers with no history of orthopaedic injury or disease participated. Both limbs were imaged and included, providing data from 500 normal knees.

The arthritic population consisted of 500 consecutive patients undergoing unilateral or bilateral TKA by two of the authors (SJM, DBC) at a private hospital in Sydney, Australia, between October 2016 and March 2018. Only operated knees were analyzed. Mean age of patients was 66 years (range 44 to 88), and were included regardless of underlying diagnosis and previous history of lower limb surgery, trauma, or deformity. In all, 310 participants (62%) in this group were female.

Radiological measurements. The normal population underwent long leg standing digital radiography using the technique described by Paley et al.¹⁹ The volunteers stood barefoot in the “stand-at-attention” position with feet together and patellae orientated forward. The radiograph beam was centred on the knee with the tube

Arithmetic HKA = MPTA – LDFA

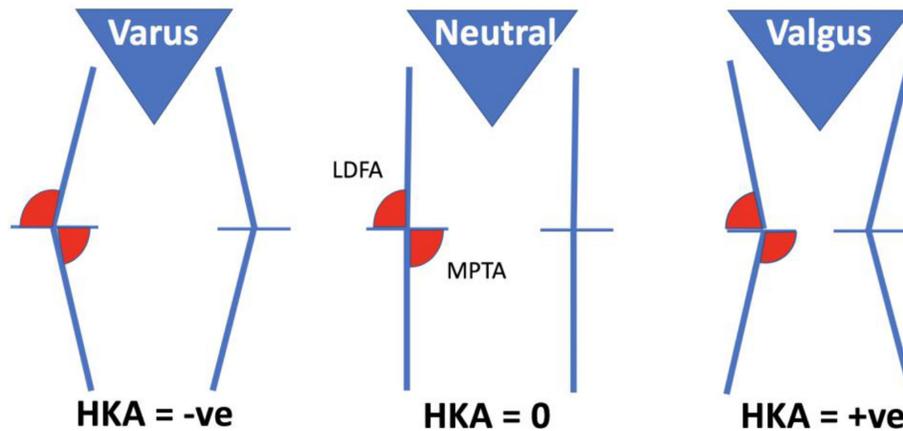


Fig. 2

Relationship between the lateral distal femoral angle (LDFA) and medial proximal tibial angle (MPTA) in varus, neutral, and valgus lower limb alignment with the arithmetic hip-knee-ankle (aHKA).

Table 1. Radiological and calculated alignment parameters for both groups.

	Normal mean, ° (SD)	Osteoarthritic mean, ° (SD)	p-value	Mean difference, ° (95% CI)
MPTA	87.0 (2.1)	87.3 (2.1)	0.070	0.3 (-0.5 to 0.0)
LDFA	87.9 (1.7)	88.1 (2.1)	0.262	0.2 (-0.4 to 0.1)
mHKA	-1.3 (2.3)	-2.9 (7.4)	< 0.001	1.6 (0.8 to 2.2)
aHKA	-0.9 (2.5)	-0.8 (2.8)	0.550	0.1 (-0.4 to 0.2)

All p-values were calculated using independent samples *t*-tests.

aHKA, arithmetic hip-knee-ankle angle; CI, confidence interval; LDFA, lateral distal femoral angle; mHKA, mechanical hip-knee-ankle angle; MPTA, medial proximal tibial angle; SD, standard deviation.

at a distance of 305 cm. Three 350 mm x 430 mm cassettes were placed immediately behind the subject and the AGFA MIMOSA VIPS 1.3.00 software package (Agfa-Gevaert, 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 where necessary. The whole pelvis was included in the radiograph.

The arthritic population underwent long leg standing digital radiography as part of their routine preoperative work-up. The radiographs were performed in a single radiology department using the same patient positioning technique as the normal group. The tube-to-knee distance was approximately 250 cm. Three 430mm x 430mm cassettes were placed behind the patient. Philips Digital Diagnostics Software (Philips Healthcare, Australia) was used for digital stitching. Kilovoltage settings varied between 70kV and 85kV per cassette. The whole pelvis was included in the radiograph.

Measurements were taken by a single observer in the normal group (JB) and by two observers in the arthritic group (DC, SM), using the following methodology, which has been shown to have high inter- and intra-observer reliability.²⁰

The centre of the femoral head was determined using digital templating with concentric circles. The centre of the ankle was defined as the midpoint of the tibial plafond. The mechanical axis (MA) of the femur was defined as the line from the centre of the femoral head to the centre of the distal femur at the knee joint. The MA of the tibia was defined as a line at the midpoint of the tibia at the level of the knee joint to the centre of the tibial plafond.

The mechanical hip-knee-ankle angle (mHKA) was defined as the angle subtended by the mechanical axes of the femur and tibia. The mHKA was expressed in degrees, with a negative value for varus alignment and a positive value for valgus alignment.

The lateral distal femoral angle (LDFA) was defined as the lateral angle between the femoral MA and the knee joint line of the distal femur. The medial proximal tibial angle (MPTA) was defined as the medial angle formed between the tibial MA and the knee joint line of the proximal tibia.

The joint line convergence angle (JLCA) was defined as the angle formed between the knee joint lines of the distal femur and proximal tibia. This was expressed as negative if the angle was formed laterally (medial joint

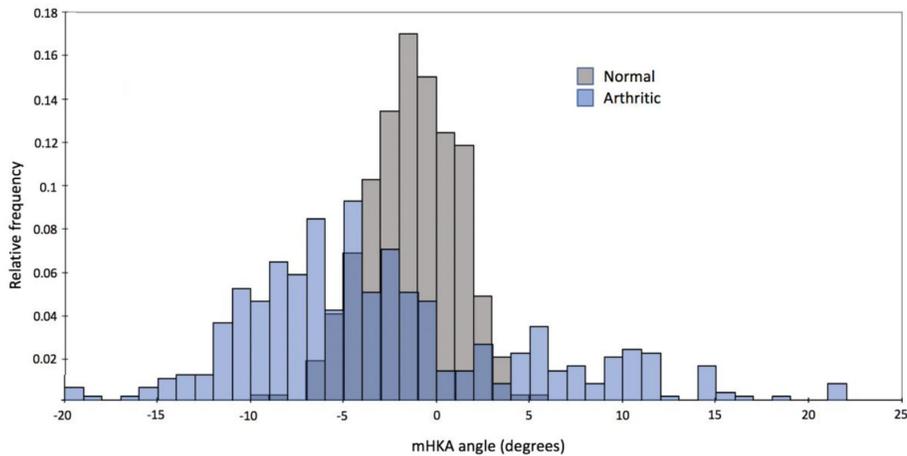


Fig. 3

Mechanical hip-knee-ankle angle (mHKA) of normal and arthritic groups showing wide variation in alignments. Negative values on horizontal axis represent varus, with positive values representing valgus.

space larger than lateral, or valgus) and positive if the angle was formed medially (varus).

The arithmetic HKA (aHKA) algorithm. Figures 1a and 1b illustrate the changes in coronal alignment and mHKA with medial compartment narrowing in degenerative arthritis. In this example, the already negative mHKA decreases further as the alignment of the limb moves farther from neutral. As Figure 1b illustrates, in the absence of significant bone loss, the LDFA and MPTA do not change in the process of joint space narrowing.

The aHKA is calculated by subtracting the LDFA from the MPTA. Figure 2 illustrates that when these two angles are equal, the aHKA is zero and the constitutional mechanical axis of the limb passes through the centre of the knee. If the LDFA is greater than the MPTA then the aHKA is negative, resulting in a constitutional varus limb alignment. If the MPTA is greater than the LDFA then the aHKA is positive, resulting in a constitutional valgus alignment of the limb.

Importantly, the calculation of the aHKA is not affected by joint space narrowing or tibiofemoral subluxation. It is also independent of the JLCA, which has been shown in a prior study of normal knees to be approximately 0.5° , and so its contribution to prediction of constitutional knee alignment has minimal clinical significance.¹ However, the mHKA does vary as asymmetric joint space loss occurs. The method makes the assumption that in a parallel joint line, the aHKA equals the mHKA. Hence, the aHKA can be used to estimate constitutional alignment.

Outcomes. To validate the aHKA concept, we analyzed the following outcomes in a stepwise fashion:

1. The mHKA of the normal group was compared to the mHKA of the arthritic group. This was to confirm that the mHKA changes with development of knee arthritic deformity.

2. The mHKA and aHKA were compared within the normal group. The aim was to determine if the aHKA produces a measurement similar to constitutional (normal) mechanical alignment of the limb.
3. The aHKA of both the normal and arthritic groups were compared. This step tested the study hypothesis that the aHKA can estimate the constitutional alignment of the limb by demonstrating a similar distribution between the groups.

Statistical analysis. Means and standard deviations (SDs) were reported for each group. Histograms with relative frequencies for each angular measure were generated for mHKA and aHKA for both the normal and arthritic groups. Two-tailed independent *t*-tests with unequal variance were used to assess differences in group means, while a matched-pairs *t*-test was used to test for differences in aHKA and mHKA within the normal subjects. Significance was set with a *p*-value 0.05. Statistical analysis was performed using SPSS Statistics 25 (IBM, USA).

Results

Table I summarizes the study's findings.

Difference in mHKA between normal and arthritic groups. There was a significant difference in means and distributions of the mHKA of normal and arthritic groups (normal mHKA mean -1.3° (SD 2.3); arthritic mHKA mean -2.9° (SD 7.4); $p < 0.001$, independent samples *t*-test). Figure 3 demonstrates this wide variation in alignments.

Difference between aHKA and mHKA in normal subjects. The mean difference between aHKA and mHKA of the normal group was 0.5° . Although this difference was statistically significant (normal mHKA mean -1.3° (SD 2.3); normal aHKA mean -0.9° (SD 2.5); $p < 0.001$, independent samples *t*-test), it was accounted for by JLCA and

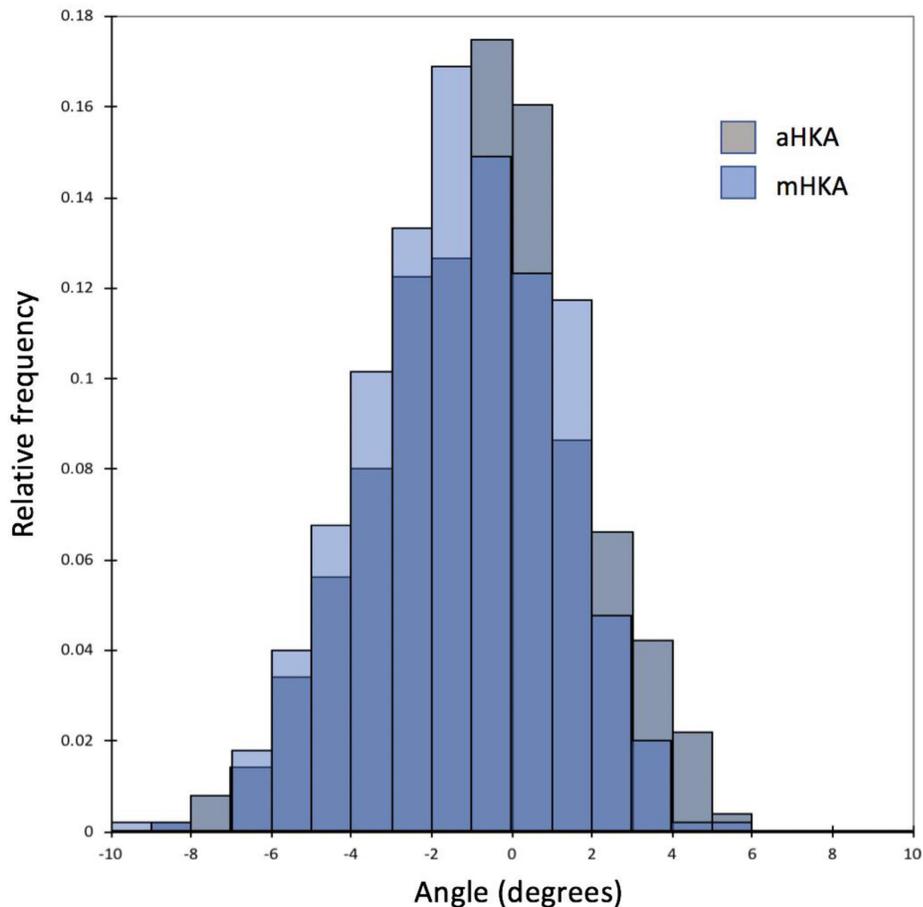


Fig. 4

Arithmetic hip-knee-ankle angle (aHKA) and mechanical hip-knee-ankle angle (mHKA) for the normal group showing similar centrality and dispersion. Negative values on horizontal axis represent varus, with positive values representing valgus.

has minimal clinical significance. Figure 4 demonstrates the similar distributions of the aHKA and mHKA within normal knees.

Primary outcome: difference in aHKA normal and arthritic groups. The mean aHKA was not statistically significant between groups (aHKA normal mean -0.9° (SD 2.5); aHKA arthritic mean -0.8° (SD 2.8); $p = 0.550$, independent samples *t*-test). Figure 5 compares the aHKA of normal and arthritic groups, showing similar centrality and distributions of alignments. There was no significant difference in the mean MPTA and LDFA between groups.

Discussion

While the distribution of the mHKA of the normal population and arthritic patients was found to be very different, the distribution of aHKA for both groups was strikingly similar. Additionally, because there was little clinically relevant variation between mHKA and aHKA within the normal group, the latter can meaningfully represent normal constitutional alignment. Hence, the study findings demonstrate that the aHKA algorithm provides an

accurate estimation of the pre-arthritic, or constitutional, alignment of the lower limb when considering large population samples.

To assess the accuracy of the aHKA on a more granular level, a previous matched-pairs radiological study analyzed the capacity of the aHKA to determine constitutional alignment.¹⁸ No significant difference was noted when comparing the mHKA of a normal limb with the aHKA of the contralateral arthritic limb in 51 patients undergoing unilateral TKA. The aHKA algorithm had a mean accuracy within 0.4° (95% confidence interval -0.8° to 0.1°) and had similar accuracy between genders. Cooke et al^{21,22} have also considered the association of the LDFA, MPTA, and JLCA (referred to as condylar-plateau angle) in relation to the HKA using long leg radiographs. However, the methods described there did not attempt to estimate constitutional limb alignment after arthritis had occurred. Other authors have also analyzed the normal limb alignment in different ethnic groups to gain a greater understanding of what is truly “normal” internationally.^{2-4,20} However, none have compared normal

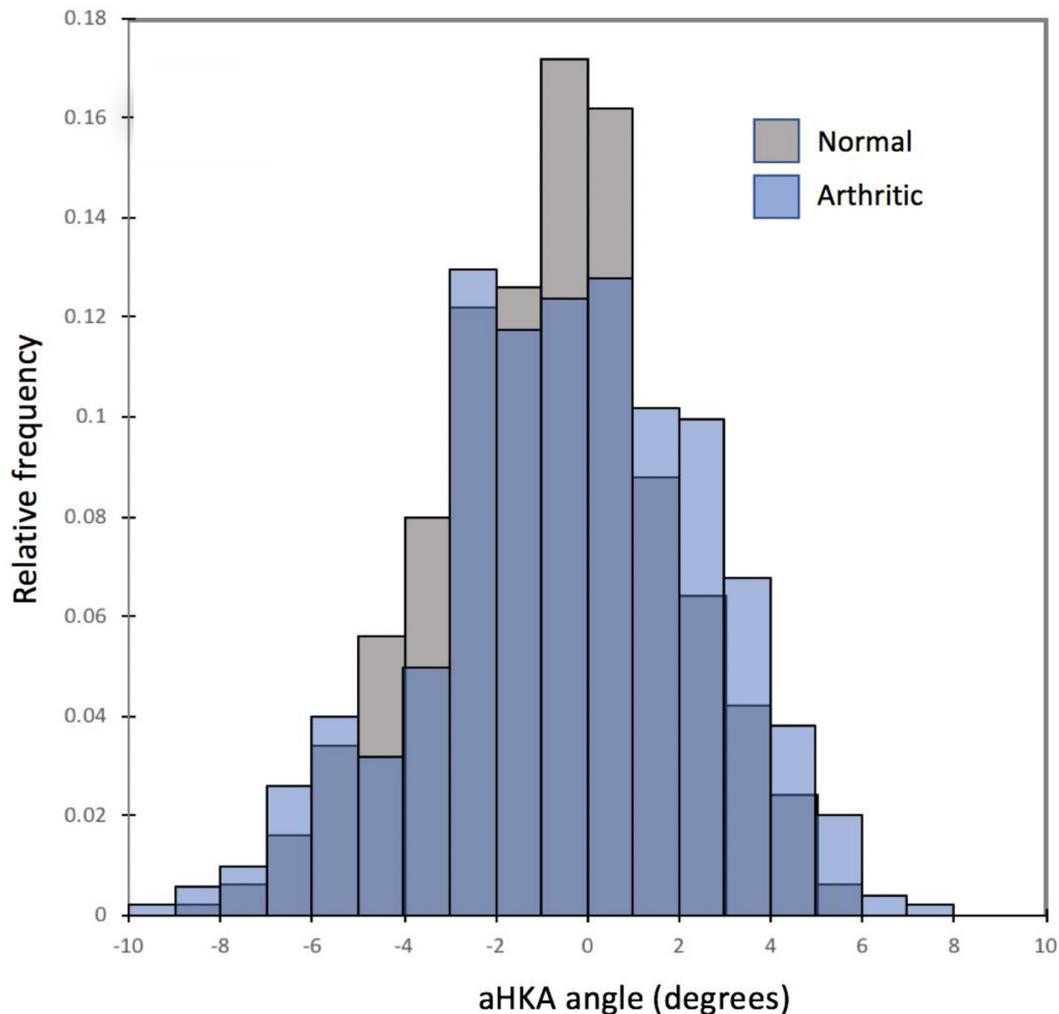


Fig. 5

Arithmetic hip-knee-ankle angle (aHKA) in normal and arthritic groups showing similar centrality and dispersion. Negative values on horizontal axis represent varus, with positive values representing valgus.

datasets to an arthritic population with application of an algorithm to approximate constitutional alignment. Compared to other studies, the distinctiveness of our normal dataset is that it is the largest cross-sectional survey undertaken to date, performed prospectively and in individuals who were within a decade of skeletal maturity.¹

It is important to note that the aHKA is only an estimation of constitutional alignment and assumes that the distal femoral and proximal tibial joint lines are parallel in the normal knee. The JLCA was measured in the normal group. The mean was -0.51° (SD 1.05), which accounts for the anatomical finding of the lateral joint space being slightly wider than the medial when the knee is in the extended position. It is possible, therefore, that the aHKA may tend to underestimate mechanical varus alignment and overestimate the valgus in normal knees. This concept can be seen in Figure 4, as the comparison between the aHKA and mHKA in the normal population shows a slight

shift of the aHKA towards the right (valgus) end of the curve. This was not felt to be clinically relevant, as 0.51° is well within the margin of error of most measurement and cutting tools. In the interest of simplicity, the JLCA has therefore been removed from the aHKA calculation.

Another limitation of the algorithm is its accuracy in the presence of bone loss, which may affect the MPTA or LDFA. The authors believe that most cases of bone loss occur at the periphery of the joint during the arthritic process, a circumstance that may have minimal impact on the aHKA calculation accuracy. The morphology of the remaining joint line allows a reasonable estimation of the degree of bone loss and allows the algorithm to provide a useful estimate of the constitutional (pre-arthritic) alignment of the limb. This is underscored by the fact that the arthritic population included in this study did not exclude patients with significant bone loss. In the most severe and advanced cases, where bone loss occurs more centrally along the joint line, the resultant changes in the

L DFA or MPTA may affect the aHKA, giving an inaccurate result.

In addition, we found a significant difference in means between the mHKA's of the normal and arthritic populations. This difference most likely represents the predominance of varus knees presenting for TKA surgery. However, the variance was significantly increased in the arthritic mHKA's due to a wide distribution of deformities, while the variance within the same arthritic population using the aHKA algorithm applied was similar to the aHKA and mHKA of the normal group.

Finally, the normal and arthritic knees populations were not matched with regard to age, geographical location, racial background or sex. In addition, in order to maximise pragmatism, we did not exclude patients in the arthritic group with prior limb surgery or deformity in the arthritic group, which may affect the algorithm's capacity to determine constitutional alignment in this subgroup. Despite this, we did not find any significant difference in the aHKA, MTPA, and L DFA between normal and arthritic knee populations. This suggests that this tool is indeed generalizable among broader population sets as a predictor of the pre-arthritic alignment.

With increasing adoption of alignment techniques, that aim to restore the constitutional limb alignment, the ability to have a practical, straightforward method to determine this key parameter is a priority for pre-surgical planning and intraoperative execution in TKA. The validation of the arithmetic HKA on a population-based level demonstrates that this algorithm can be used to estimate constitutional alignment of the lower limb following the onset of arthritis. This tool will be of particular interest to surgeons aiming to restore their TKA patients to a pre-arthritic alignment.



Take home message

- The arithmetic hip-knee-ankle (aHKA) provides a practical, straightforward method for estimating constitutional (pre-arthritic) lower limb alignment after the development of arthritic deformity.
- This study describes and validates the use of the aHKA algorithm for preoperative planning and intraoperative restoration of constitutional alignment.
- The tool will be of particular interest to surgeons aiming to restore their total knee arthroplasty patients to a pre-arthritic alignment.

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Author contributions:

- W. Griffiths-Jones: Conceived and designed the study, Analyzed the data, Wrote and approved the manuscript.
- D. B. Chen: Designed the study, Wrote and approved the manuscript.
- I. A. Harris: Interpreted the data, Wrote and approved the manuscript.
- J. Bellemans: Wrote and approved the manuscript.
- S. J. MacDessi: Conceived and designed the study, Analyzed and interpreted the data, Wrote and approved the manuscript.

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