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The dynamic nature of alignment and variations in normal knees

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The restoration of knee alignment is an important goal during total knee arthroplasty (TKA). In the past surgeons aimed to restore neutral limb alignment during surgery. However, previous studies have demonstrated alignment to be dynamic, varying depending on the position of the limb and the degree of weight-bearing, and between patients. We used a validated computer navigation system to measure the femorotibial mechanical angle (FTMA) in 264 knees in 77 male and 55 female healthy volunteers aged 18 to 35 years (mean 26.2). We found the mean supine alignment to be a varus angle of 1.2° (standard deviation (SD) 4), with few patients having neutral alignment. FTMA differs significantly between males and females (with a mean varus of 1.7° (SD 4) and 0.4° (SD 3.9), respectively; p = 0.008). It changes significantly with posture, the knee hyperextending by a mean of 5.6°, and coronal plane alignment becoming more varus by 2.2° (SD 3.6) on standing compared with supine.

Knee alignment is different in different individuals and is dynamic in nature, changing with different postures. This may have implications for the assessment of alignment in TKA, which is achieved in non-weight-bearing conditions and which may not represent the situation observed during weight-bearing.

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Coronal plane alignment is an important determinant of success following total knee arthroplasty (TKA).[1-4] Traditionally, the goal during TKA has been to create a neutral femorotibial mechanical angle (FTMA), which can be achieved using conventional instrumentation or by newer methods, including computer-assisted navigation or patient-specific instrumentation (PSI).[5-11] However, in spite of the greater accuracy afforded by these advances, a substantial proportion of patients (up to 20%) are dissatisfied following TKA.[12-14]

There are wide variations in limb alignment between individual patients: when measured using CT only 2% of normal limbs have a neutral mechanical axis, and as many as 76% deviate from neutral by > 3°.[15] Limb alignment differs between males and females: a study of full-length lower limb radiographs by Bellemans et al[16] showed 32% of male and 17.2% female knees to be in > 3° of constitutional varus. As such, the establishment of a neutral mechanical axis following TKA may not represent a correction to 'normal' alignment.[15-17] The situation is further complicated by differences in the alignment of the limb when measured in a lying position (which is non-weight-bearing) and in a weight-bearing standing position.[18]

A more detailed understanding of the extent of variation in alignment in normal patients may improve outcomes after TKA. Whereas most previous studies have investigated the alignment of knees with osteoarthritis (OA) and those following TKA, it is important to understand how the mechanical axis varies among knees that are free of disease. Likewise, most studies have investigated lower limb alignment using exclusively either supine or standing radiographs, and it is not clear whether the measurement of alignment in the two positions is comparable between different studies.

The aim of this study was to evaluate the FTMA in healthy volunteers using computer navigation. We aimed to quantify the variation with changes in side, posture and gender using the same device for serial measurements at the same session.

Patients and Methods

Before starting the study, a power calculation was performed, based on data from a previous study using the same system.[19] In order to detect a mean difference of 1° (standard deviation (SD) 2.5), with an alpha of 0.05 and power of 80%, it was calculated that at least 100 knees would be needed in each group.

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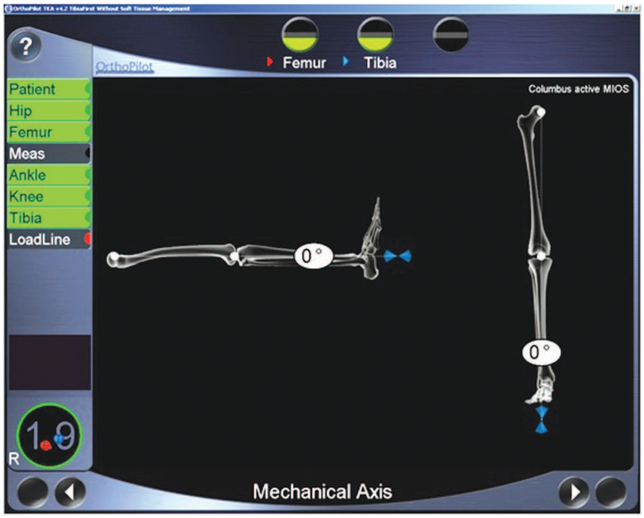

Fig. 1

Computer screen showing alignment on coronal and sagittal planes.

Fig. 2

Photograph showing registration of the hip centre in progress.

This study was carried out between six centres with the aim of capturing the greatest possible diversity of subjects. Healthy volunteers aged between 18 and 35 years were recruited. Patients with a history of knee or leg pain, those with known abnormalities of alignment, developmental dysplasia or previous trauma, and those with a family history of malalignment or dysplasia were excluded. A total of 289 knees were tested in 157 subjects; 25 subjects were excluded because one or other side hip centre could not be acquired and hence alignment could not be recorded. Therefore, a total of 264 knees in 132 subjects were included in the analysis: there were 77 men (154 knees) and 55 women (110 knees) with a mean age of 26.2 years (SD 4.4).

In each patient the FTMA was measured with a validated method using an infrared-based navigation system (Orthopilot, B Braun, Tutlingen, Germany), with reference arrays attached to the patient using fibroelastic straps[19-21] (Figs 1 and 2). All measurements were taken by a single surgeon who had experience of > 1000 navigated arthroplasties (KD) and who travelled to each centre to take the measurements.

To allow the system to determine the FTMA, the centres of the head of the femur, the knee and the ankle were acquired first, using a similar method to that used during knee arthroplasty with the Orthopilot system. The centres of the hip and the knee were acquired using a kinematic method, whereby the hip is rotated and the knee flexed and extended to allow the computer to determine the centre of the arc of movement. The centre of the ankle was registered anatomically using the most prominent parts of the medial and lateral malleoli, and the transverse plane of the knee was calculated in a similar fashion using the positions of the two epicondyles of the femur. The FTMA was measured with the patient supine with the knee in 0° and 15° flexion, and the range of movement from full extension to full flexion was recorded. The subject was then asked to stand in bipedal and monopedal stances and the FTMA and sagittal plane extension position were measured in both postures.

Statistical analysis. Differences in FTMA in extension and flexion in both bipedal and monopedal stance were analysed using paired Students *t*-test as the data were normally distributed. The gender and side variations were also assessed using the same test. Neutral was defined as 0° FTMA. In common with previous studies[16] constitutional varus was defined as a varus > 3°. Results are presented as mean and SD; a p-value < 0.05 was considered significant. Statistical analysis was performed using SPSS version 19software (IBM Inc., Armonk, New York).

Results

With the subject supine, the mean FTMA was 1.2° (SD 4) varus at full extension, and 1.1° (SD 4.2) varus at 15° flexion (p = 0.94). In all, 156 of 264 knees (59%) were within 3° of neutral, 74 of 264 knees (28%) were in constitutional varus (> 3°), 31 (11.7%) were in complete neutral (0°) and 34 (12.9%) knees were in valgus of more than 3°. FTMA ranged from 13° varus to 13° valgus. Two knees were in more than 10° varus and one in more than 10° valgus. Compared with the alignment while supine, the mean FTMA was 2.2° (SD 3.6) further varus in the bipedal weight-bearing stance (p < 0.001) and 3.4° (SD 3.8) further varus in the monopedal weight-bearing stance (p < 0.001). If knees were supine, varus, or < 2.5° valgus, they became more varus on standing, but knees of > 2.5° valgus tended to become more valgus on standing (Fig. 3).

The mean range of movement was 146.3° (SD 10.4) of flexion, with a mean of 3.2° (SD 5.8) of hyperextension. On standing, in the sagittal plane the degree of extension increased by 5.6° (SD 6.8) in bipedal stance (p < 0.001) and by 5.6° (SD 7.7) in monopedal stance (p < 0.001). There was no statistically significant difference in the degree of extension observed between the two stances (p = 0.90).

Table I. Changes in mechanical axis measured in supine, weight-bearing bipedal and weight-bearing monopedal stances (difference measured using Paired *t*-test)

	Supine FTMA Mean (SD)	n (%) in > 3° varus	Standing bipedal FTMA change	Standing monopedal FTMA change
All (264 patients)	Varus 1.2°(4°)	74 (*28*)	Varus 2. (3.6°) p < 0.001	Varus 3.4° (3.8°) p < 0.001
Men (154)	Varus 1.7° (4°)	52(*33.7*)	Varus 2.4°(3.7°) p < 0.001	Varus 3.6° (4.1°) p < 0.001
Women (110)	Varus 0.4° (3.9)	22 (*20*)	Varus 1.8° (3.) p < 0.001	Varus 3.2° (3.3°) p < 0.001

SD, standard deviation; FTMA, Femorotibial mechanical axis

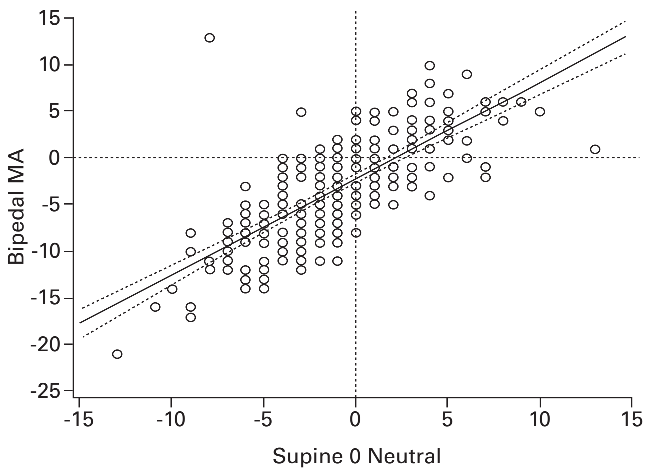

Fig. 3

Correlation of femorotibial mechanical axis in supine (horizontal axis) and bipedal mechanical axis (MA) in standing position. Positive value represents valgus and negative represents varus alignment.

Supine, and in full extension, the mean FTMA was 1.7° (SD 4) varus in men, compared with 0.4° (SD 3.9) varus in women (p = 0.008): in all 52 of the 154 men (33.7%) were in > 3° of varus compared with 22 of 110 (20%) women (Table I). In the same setting, the FTMA of right legs was 0.5° (SD 4.1) varus, compared with 1.8° (SD 3.8) varus in left legs (p = 0.007). There was no statistically significant difference between younger patients (< 25 years) and older patients. The mean FTMA of younger patients was 0.9° (SD 3.86) varus, compared with 1.48° (SD 4.08) varus in older patients (p = 0.24).

Discussion

The aims of this study were to evaluate the FTMA in healthy volunteers and to assess the level of variation with gender, side and position (supine, monopedal and bipedal stance). This study has demonstrated a wide variation in FTMA with a mean alignment of 1.2° (SD 4) varus, even among healthy individuals with functionally normal knees. To the best of our knowledge this is the largest study to date using non-invasive kinematic navigation to measure FTMA in non-arthritic knees.

There are limitations to our study. It was based on the extracutaneous attachment of trackers which may not be as accurate as using bony attachments as may be a possibility looking at difference in right and left sides. The use of such attachments has been validated in previous studies using same method, and the use of bony attachments is not viable in the setting of normal volunteers.[19-21] One previous study recorded inter- and intra-registration measurement errors of this system, finding errors of up to 1°,[19] which is why this minimum difference was used in the power calculation. We did not measure the intra-registration measurement error in this study, and as the system is operator dependent, the degree of error may differ from that recorded in previous studies. The transepicondylar axis was detected using manual palpation of the epicondyles, which may be a further source of error. However, this is unlikely to affect the measurements when taken in > 40° of flexion, as was the case in this study.[20] The change in the disposition of underlying muscle mass with flexion could also affect the measurements by displacing the trackers when the knee in cycled through flexion, although the flexion measurements were only small part of our study. All of the units participating in this study were in the same country, and there may be differences in limb alignment between subjects of different countries which are not apparent in our study cohort. Alignment is likely to be different in knees with osteoarthritis and those that have undergone TKA, neither of which were included in this study.

In most cases, limb alignment is measured using clinical evaluation and radiographs centred on the knee joint. However, such estimates may be inaccurate by as much as ±5°.[22, 23] Even with full-length hip–knee–ankle radiographs there may be errors due to changes in limb position, resulting in apparent variations in alignment produced by flexion at the knee or rotation at the hip.[24] The use of CT overcomes many of these problems by providing a three-dimensional evaluation of lower limb anatomy, but is unable to provide weight-bearing information. Both modalities also have the disadvantage of involving exposure to ionising radiation.

Computer-assisted navigation is designed to provide surgeons with quantitative measurement tools for real-time assessment of lower limb alignment and kinematics.[25-27] This study used a similar infra-red based computer navigation system to measure FTMA, with a method that had previously been validated.[19-21] This method of measurement has a number of potential advantages over other measurement systems. The immediate generation of real-time onscreen coronal and sagittal FTMA angles enables dynamic measurements of alignment to be made on weight-bearing, with immediate visualisation of angular displacement. The system can be used in the clinic setting and does not involve ionising radiation. In the setting of knee replacement, the use of pre- and intra-operative computer navigation may help the surgeon set more appropriate goals for alignment and kinematics in individual patients.

The principal finding of our study is that the majority of normal people do not have a neutral mechanical axis. Using different methods, previous authors have reported similar findings. Eckhofff et al[15] performed CTs in 180 healthy legs in a supine position and found a mean deviation in FTMA of 2.7° (SD 2.6) from the neutral. Bellemans et al[16] reported the mean FTMA to be 1.3° varus (SD 2.34). The absolute values in our study are slightly different, which may be explained by differences in the patients studied, postural variation or potential errors due to measurement methods used in our or their studies.

A change in coronal alignment with standing has previously been demonstrated in osteoarthritic knees.[18] Our study has demonstrated a similar effect in normal knees, with patients who are varus or up to 2.5° valgus while supine, tending to become more varus (as well as hyperextending) on standing. This is similar to the effect reported by Clarke et al,[28] who demonstrated that normal, osteoarthritic and post-TKA knees all tended to hyperextend and become more varus in a standing position compared to supine. The authors concluded that the consistent kinematic pattern for the three groups suggested that soft tissue constraints, rather than underlying joint deformity, are more influential in the control of alignment from lying to standing.[28] Likewise, our finding of a difference in alignment between men and women is similar to that reported by Bellemans et al,[16] who report a mean FTMA for men of 1.9° varus and for women 0.8 ° varus, similar to our findings of 1.7° and 0.4°, respectively. They also demonstrated a similar proportion (32% in men, 17% in women) having a constitutional varus > 3° (in our study, the proportions were 34% and 20%, respectively). Perhaps women have less varus compared with men because of relatively smaller heights and length of femur.

The findings of this study may have implications for surgeons performing TKA. During TKA, surgeons aim to create a neutral mechanical axis to achieve uniform medial and lateral loading of the polyethylene insert, a process which is facilitated using navigation. The results of this study suggest that, even if neutral alignment is achieved intra-operatively, this may translate to a varus alignment with weight-bearing. Therefore, there may be a theoretical advantage in aiming for 1º to 2º of valgus in order to accommodate this change. It may be more appropriate to restore an individual patient's native alignment at TKA than create a neutral FTMA.[29] However, the biomechanical state of the replaced knee is different from that of the normal knee, and on the basis of this study we cannot make such a recommendation. These questions should be addressed in further studies.

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K. Deep, study design, data collection, writing paper, revising paper.
K. K. Eachempati data collection, contribute to writing paper.
S. Apsingi, data collection, contribute to writing paper.
B. Braun Aeculap provided the equipment and logistics support for carrying out the study.

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