Arthroplasty Today 18 (2022) 16–23

Contents lists available at ScienceDirect

Arthroplasty Today

journal homepage: http://www.arthroplastytoday.org/

Original Research

Functional Femoral Anteversion: Axial Rotation of the Femur and its Implications for Stem Version Targets in Total Hip Arthroplasty

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ARTICLE INFO

Article history:
Received 20 April 2022
Received in revised form
13 August 2022
Accepted 6 September 2022
Available online xxx

Keywords:
Functional femoral anteversion
Femoral rotation
THA
Pelvis-femur relationship
Axial rotation
Functional alignment

ABSTRACT

Background: Acetabular and femoral component positioning are important considerations in reducing adverse outcomes after total hip arthroplasty (THA). Previous assessments of femoral anteversion examined anatomic femoral anteversion (AFA) referenced to anatomic landmarks. However, this does not provide a functional understanding of the femur's relationship to the hip. We investigate a new measurement, functional femoral anteversion (FFA), and sought to measure its variability across a large sample of patients undergoing THA.
Methods: A total of 1008 consecutive patients underwent THA surgery between September 2019 and July 2021. All patients were measured for supine and standing functional femoral rotation (FFR), AFA, and FFA.
Results: The mean standing FFA was 13.2° ± 12.2° (−27.8° to 52.3°). The mean change in FFR from supine to standing was −2.2° ± 11.8° (−43.0° to 41.9°). Of all, 161 (16%) patients had standing FFA version greater than 25°. Four hundred sixty (46%) patients had standing FFR (internal or external) greater than 10°. One hundred twenty-three (12%) patients exhibited an increase in external rotation from supine to standing of greater than 10°. A moderate, negative linear relationship was observed between AFA and standing external femoral rotation (*P* <<.001, R = −0.46), indicating people may externally rotate their femur as AFA decreases with age.
Conclusions: Functional alignment of the femur in patients requiring THA is understudied. It is now understood that the femur, like the pelvis, can rotate substantially between functional positions. Enhancing our understanding of FFA and FFR may improve both acetabular and femoral component positioning.

Introduction

Acetabular cup positioning has long been recognized as an important consideration in total hip arthroplasty (THA) [1-6]. Malpositioning of the acetabular cup has been shown to lead to increased rates of wear, edge loading, and impingement which may lead to instability, osteolysis, or dislocation [1-6].

Lewinnek et al. were among the first authors to recognize the relationship between acetabular cup positioning and dislocation rates by proposing a widely cited "safe zone" [7] that was believed to reduce the incidence of dislocation. However, further examination in larger samples of THA patients revealed that it does not preclude dislocation [8,9] and is insufficient for surgical guidance.

Assessments of pelvic tilt in functional positions, when edge-loading and impingement are most likely [6,10], later revealed large interindividual variability between positions [11-13], with pelvic rotation between positions as low as 5° and as high as 70°. These changes in pelvic tilt would correspond to changes in acetabular anteversion of 4° and 50°, respectively, [14] and help explain why some individuals with a given cup orientation dislocate while others with the same cup orientation do not.

Similar to the variability of pelvic tilt, investigations into anatomic femoral anteversion (AFA) revealed large variability

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https://doi.org/10.1016/j.artd.2022.09.002
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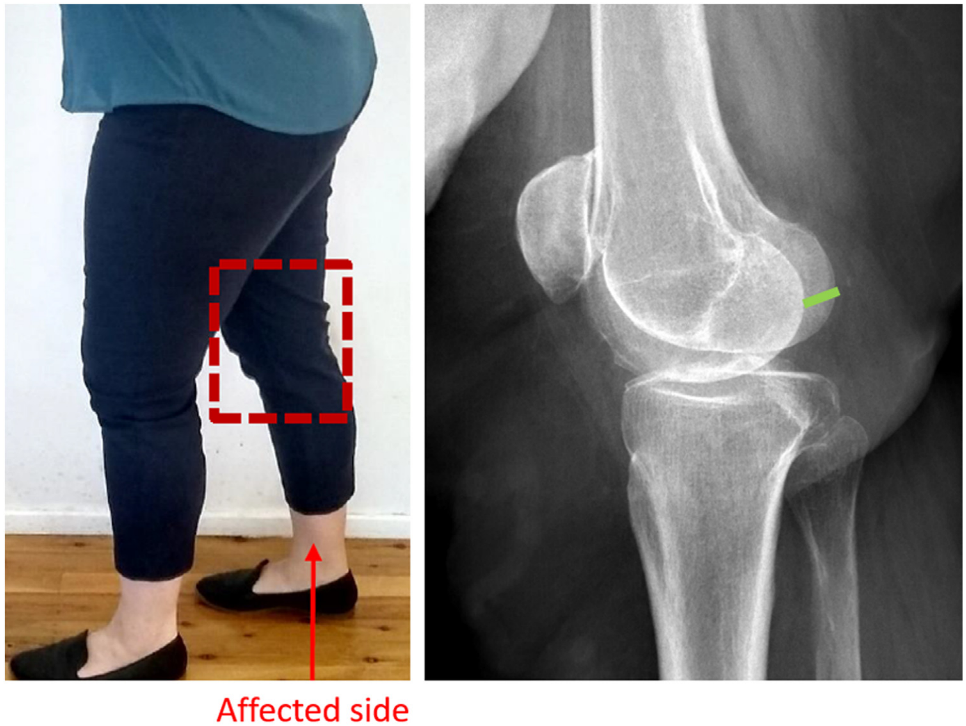

Figure 1. (Left) The stance taken by a patient while undergoing their preoperative functional knee radiology. (Right) Functional knee radiograph acquired preoperatively to enable calculation of the patient's standing functional femoral rotation.

[15-18], ranging up to 80° [18]. Gender and age differences were also observed, with AFA decreasing for males as age increases [18]. These studies measured AFA as the angle between the femoral neck and the posterior condylar line (PCL) projected onto the axial plane [15,17,19] or onto a plane perpendicular to the long femoral axis [18]. This measurement references only anatomic landmarks and is constant between different patient positions as it does not account for functional femoral rotation (FFR). However, supine and standing FFR have been shown to vary significantly between individuals [20,21] and change from presurgery to postsurgery following THA [20]. These rotational changes would alter the functional stem anteversion (FSA) of an implanted femoral component and thus have implications for the optimal femoral stem target. Specifically, individuals who exhibit a high internal FFR may be at risk of anterior impingement when anatomic stem anteversion (ASA) is low or negative, and individuals who exhibit a high external FFR may be at risk of posterior impingement when ASA is high.

Therefore, the aims of this study were three-fold: first, to further investigate the variability of a new measurement proposed by Uemura et al. [22] called functional femoral anteversion (FFA) across a larger sample of patients undergoing THA; second, to assess its implications for femoral stem version targets; third, to investigate the number of individuals whose FFR would transition them out of suggested combined anteversion (CA) zones.

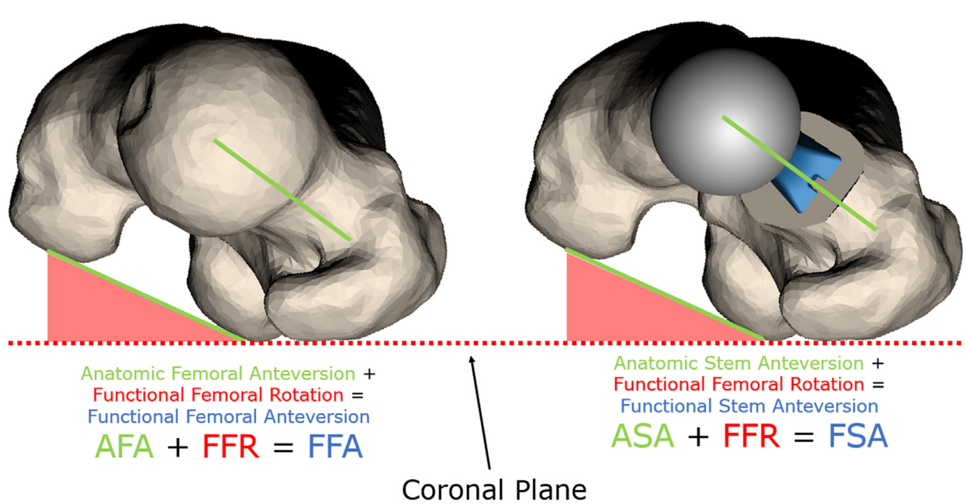

Figure 2. Left: Illustration of the relationship between anatomic femoral anteversion, functional femoral rotation, and functional femoral anteversion. Right: Illustration of the relationship between anatomic stem anteversion, functional femoral rotation, and functional stem anteversion using 3D templating to recreate the anatomic femoral anteversion.

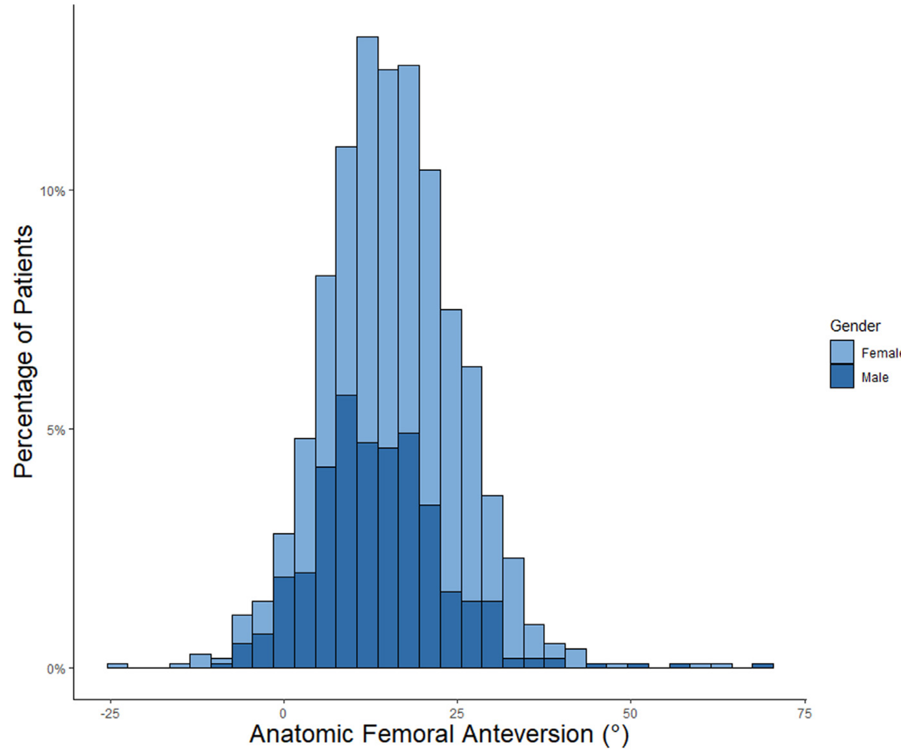

Figure 3. Histogram of the anatomic femoral anteversion results.

Material and methods

A total of 1008 consecutive patients underwent THA surgery between September 2019 and July 2021. Of the total, 627 were female (62%), and the average age was 66 years (16-95). Inclusion criteria included patients that had a long-limb computed tomography (CT) scan and standing lateral X-ray of the distal femur (Fig. 1) as a part of the 360 Med Care (Sydney, Australia) THA preoperative planning protocol. The lateral knee radiograph taken was previously not standardized and, as far as the authors are aware, not routinely taken for any other preoperative THA planning protocol. However, our imaging protocol contains detailed instructions for radiographers to position the patient and acquire the imaging, and all radiology centers must be approved via an in-person explanation of the protocol. We believe these steps ensure repeatable lateral knee radiographs of patients in standing and permit accurate measurement of their FFR. From these imaging data, assessments were made for supine and standing FFR, defined as the angle between the PCL and the coronal plane and for AFA, defined as the angle between the femoral neck and the PCL, projected onto the femoral anatomic axis.

AFA was measured using the approach described by Pierrepont et al. [18]. The CT scan was segmented in ScanIP Medical (Simpleware; Synopsys, Exeter, United Kingdom) to recreate 3D models of the patient's bony anatomy. Landmarks on the operative side were measured to establish the PCL and the femoral neck axis. Supine FFR was measured in RadiAnt DICOM Viewer v2.2.5.10715 (Medixant, Poznan, Poland) on CT scans with a line that was tangential to the posterior femoral condyles and a horizontal baseline. Standing FFR was measured by first taking the sagittal distance between the posterior condyles on the lateral knee radiograph. A computational algorithm then recreated this distance in 3D using a segmented model of the patient's femur and modified the femoral rotation, measured against the coronal plane, until the length of the PCL converged to the value previously measured. This is equivalent to calculating the FFR required to make the PCL and coronal plane parallel. Positive FFR values were interpreted as external rotation. Therefore, adding the FFR to the AFA resulted in FFA. A visual representation of the relationship among AFA, FFR, and FFA can be found in Figure 2, which also shows the FSA by using 3D templating to recreate AFA.

A positive change in FFA from the supine to standing position was interpreted as external rotation of the femur between these positions. All imaging and measurements were evaluated twice by qualified surgical planning engineers.

Table 1
Tabulated results for all 1008 consecutive patients across supine femoral rotation, anatomic femoral anteversion, standing functional femoral rotation, standing functional anteversion, and the change in functional femoral rotation from supine to standing.

▪	Mean (absolute mean)	Range	Standard deviation	*P* value (difference between genders)
Supine femoral rotation	0.4°	−34.0° to 31.4°	10.6°	<<.001[a]
Anatomic femoral anteversion	15.6°	−24.4° to 68.4°	9.8°	<<.001[a]
Standing functional femoral Rotation	−2.6°	−46.0° to 37.0°	13.1°	<<.001[a]
Standing functional femoral anteversion	13.1°	−27.8° to 52.3°	12.2°	<<.001[a]
Change in functional femoral rotation (supine to standing)	−2.2° (8.7°)	−43.0° to 41.9°	11.8°	.18

[a] Indicates statistical significance.

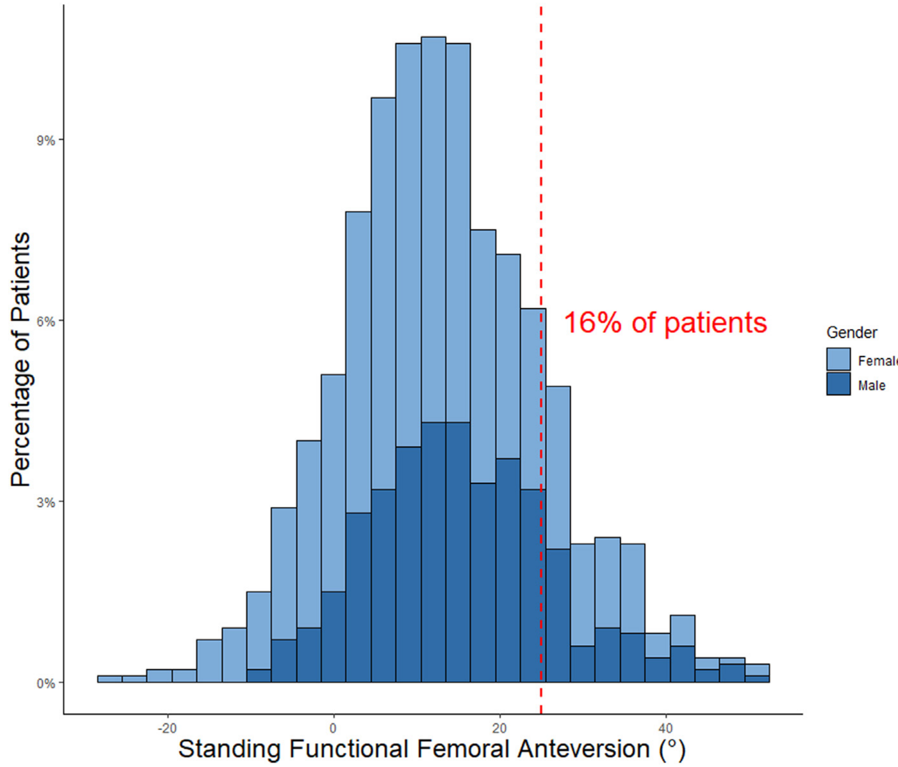

Figure 4. Histogram of the standing functional femoral anteversion results. Sixteen percent of patients had functional femoral anteversion greater than 25°, which may place them at risk of functional malorientation when considered in the context of combined anteversion.

Statistical analysis

Statistical analysis was performed in RStudio v1.3.1903 (RStudio, Boston, MA). An alpha value of 0.05 was used to determine clinical significance. Two-way t-tests were used to determine significant differences in continuous variables. Pearson's correlations were used to assess the linear relationship between continuous variables.

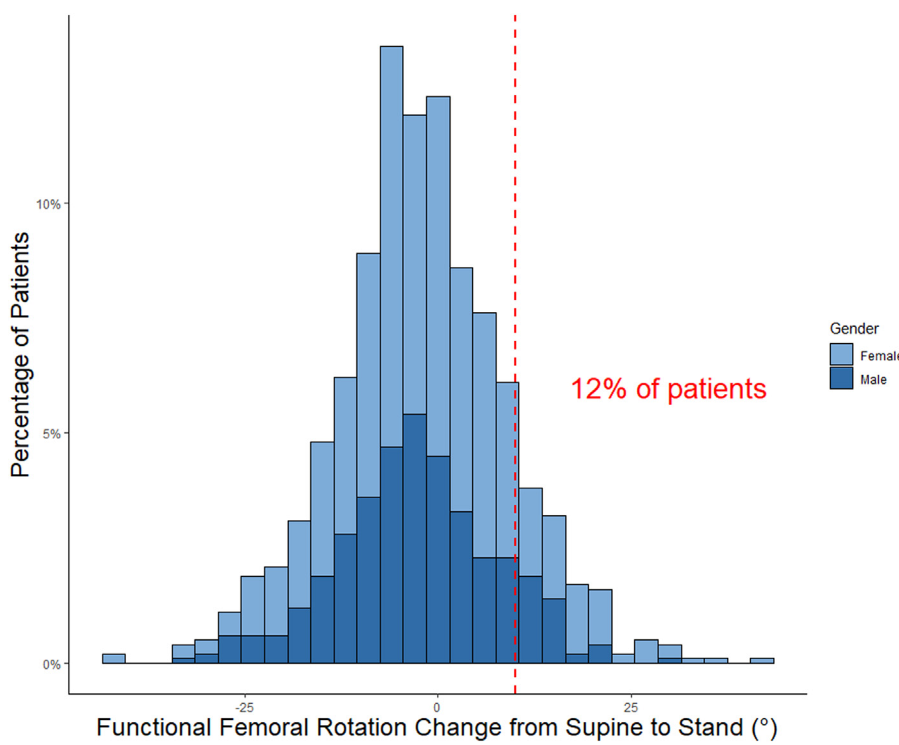

Figure 5. Histogram of the change in functional femoral rotation results. Twelve percent of patients exhibited external femoral rotation of greater than 10° from supine to standing position, which may place them at risk of functional malorientation.

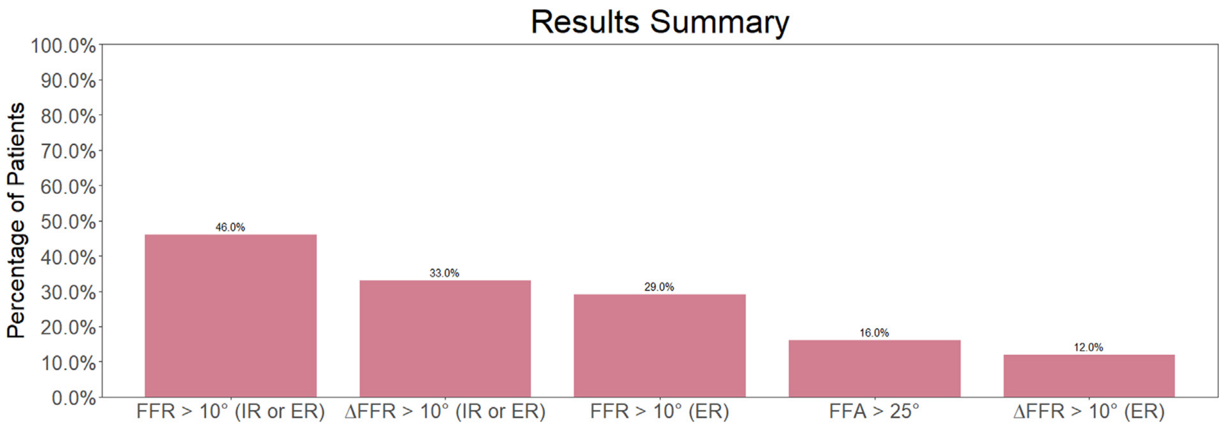

Figure 6. Summary of the key findings for FFR and FFA. ER, external rotation; IR, internal rotation.

Ethics

This retrospective analysis was approved by the Bellberry Human Research Ethics Committee (study number 201203710).

Results

Results for the supine and standing FFR, AFA, standing FFA, and the change in FFA from supine to standing are given in Table 1 and Figures 3-6. The mean supine FFR was 0.4 ± 10.6° (−34.0° to 31.4°). There was a significant gender difference ($P << 0.001$) with a mean supine FFR of 3.3° (−31.4° to 31.4°) for females and −4.5° (−34.0° to 24.5°) for males. The mean AFA was 15.6° ± 9.8° (−24.4° to 68.4°), and significant gender differences were observed ($P << 0.001$). The mean AFA was 16.8° (−24.4° to 63.6°) for females and 13.8° (−9.4° to 68.4°) for males. The mean standing FFR was −2.7° ± 13.1° (−37.0° to 46.0°), and significant gender differences were observed ($P << 0.001$). The mean standing FFR was −5.2° (−37.0° to 46.0°) for females and 1.7° (−34.0° to 35.7°) for males, indicating that, while standing, females tend to be internally rotated and males tend to be externally rotated. The mean standing FFA was 13.2° ± 12.2° (−27.8° to 52.3°), and significant gender differences were observed ($P << 0.001$). The mean standing FFA was 11.7° (−27.8° to 52.3°) for females and 15.6° (−8.5° to 49.9°) for males. The mean change in FFR from supine to standing was −2.2° ± 11.8° (−43.0° to 41.9°), and no significant gender differences were observed ($P = .18$). The absolute mean change in FFR from supine to standing was 8.7° ± 7.2° (−0° to 43.0°), and no significant gender differences were observed ($P = .09$).

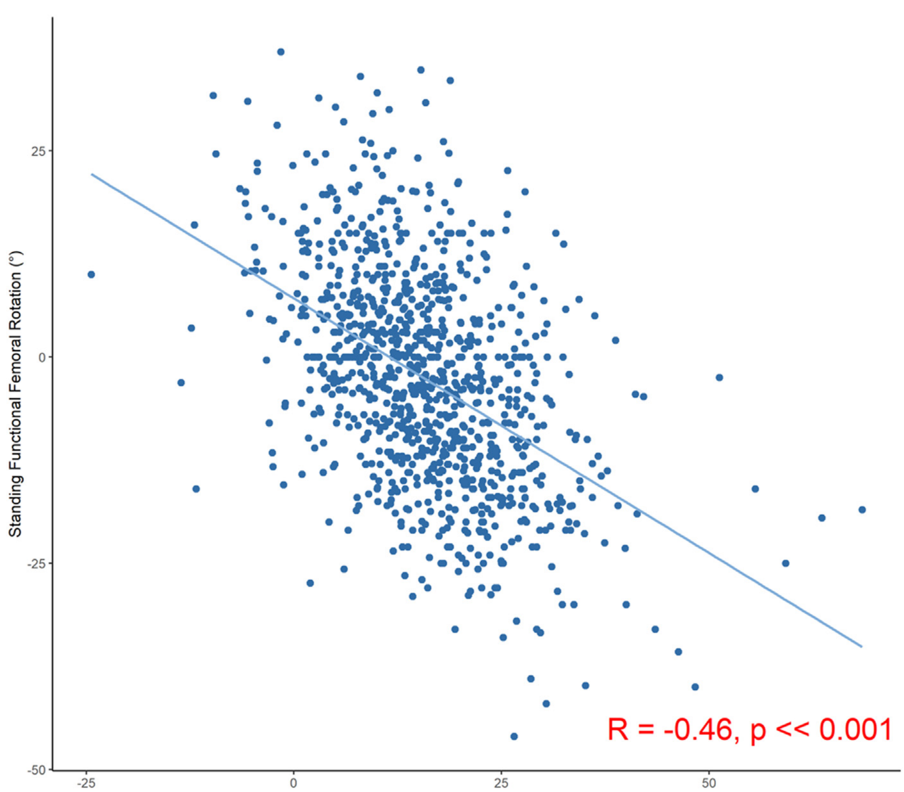

Figure 7. Scatter plot of standing functional femoral rotation and anatomic femoral anteversion and the correlation between these. The statistically significant negative relationship indicates that people may externally rotate their femur as their anatomic femoral anteversion decreases as a compensatory mechanism to maintain soft-tissue tensioning.

One hundred sixty-one (16%) patients had standing FFA version of greater than 25° (Figs. 4 and 6). Considering a CA zone of 25°-45° and a conventional standing cup anteversion of 20°, 72% of patients would fall within the CA zone when anatomic femoral landmarks are considered (AFA), but only 59% fall within the zone when the functional position of the femur (FFA) is considered. Therefore, considering FFA would place an additional 13% of patients at risk of posterior impingement in a widely targeted CA zone. Four hundred sixty (46%) patients had a standing FFR (internal or external) greater than 10° (Fig. 6). One hundred twenty-three (12%) patients exhibited an increase in external rotation from supine to standing of greater than 10° (Figs. 5 and 6). Three hundred thirty-five (33%) patients exhibited an absolute change in FFR (internal or external rotation) of greater than 10° (Fig. 6). These patients' femoral components would be functionally oriented in an alignment that is considerably different to the alignment when the prosthesis is implanted on the operating table, or when only AFA is considered, and may place them at risk of functional malorientation.

A weak but significant relationship was found with older patients exhibiting less AFA ($P << 0.001$, $R = -0.17$); greater standing FFR ($P << 0.001$, $R = 0.18$); and greater change in FFA from supine to standing ($P << 0.001$, $R = 0.17$). A moderate, negative linear relationship was also observed between AFA and standing FFR ($P << 0.001$, $R = -0.46$), indicating people may externally rotate their femur as AFA decreases with age (Fig. 7).

Discussion

Functional alignment of the femur in patients requiring THA is understudied. Several studies have previously investigated AFA [15-18] and how this presents across samples of patients undergoing THA. However, it is known that there is large variation in FFR among individuals and from presurgery to postsurgery [20,21], which AFA does not capture. In this study, we sought to further investigate FFA, a new measurement explored by Uemura et al. [22], across a larger sample of patients undergoing THA, assess its implications for femoral stem version targets, and investigate the number of individuals whose femoral rotation may place them at risk of malorientation.

Our results of a mean supine femoral rotation of 0.4° ± 10.6° are similar to those of studies by Uemura et al. [21,22] who observed median supine femoral rotations of −0.4° ± 10.9° (n = 324) and 0.3° ± 8.3° (n = 191). Both studies by Uemura et al. [21,22] and our study demonstrate that, despite having a mean supine rotation value near neutral, the PCL cannot be used as a reference for measuring FFA due to significant interpatient variability. Additionally, we have shown that supine FFR can be over 40° different from standing FFR, 46% of patients have significant standing FFR (>10° internal or external), and 33% of patients undergo significant changes in FFR (>10° of rotation) between positions. Therefore, standing FFR and FFA should not be assumed to be similar to supine FFR.

Our results of a mean AFA of 15.6° (−24.4° to 68.4°) with significant gender differences and the property of decreasing with age are comparable to previous assessments of AFA. In a study of 1215 patients requiring THA, Pierrepont et al. found a median AFA of 14.4° (−27.1° to 54.5°) with significant gender differences and the property of decreasing with increasing age for males [18]. Similarly, Hartel et al. found a median AFA of 14.2° (−23.6° to 48.7°) and significant gender differences across 1070 patients [17].

As far as the authors are aware, previous investigations of standing FFR and the change in FFR from supine to standing are limited to 1 study by Uemura et al. [22]. This paper, which assessed preoperative and postoperative AFA and FFR, found a mean preoperative supine FFR of 0.3° ± 8.3°, mean preoperative standing FFR of −4.5° ± 8.8°, and significant changes between preoperative and postoperative states. However, this study did not explore the implications of femoral rotation regarding soft-tissue tensioning around the joint or stem version targets, and its findings may be limited to a Japanese population, with the mean AFA of 25.6° ± 10.6° being significantly higher than that reported in previously published studies [15-18].

Regarding the soft-tissue consequences of femoral rotation, we found a moderate correlation whereby decreasing AFA (which is correlated with increasing age) was associated with increasing external FFR in standing. This indicates the possibility of a compensatory mechanism occurring around the joint where the functional positioning of the femur corrects for anatomical variations, which could be occurring to maintain tension in the soft tissue around the capsule. Specifically, an individual's FFA may remain roughly constant over time, but their FFR may increase to compensate for a decrease in their AFA. Consequently, large intraoperative changes to ASA may result in subsequent FFR changes, altering the patient's postoperative functional CA and/or soft-tissue tensioning. Similar ideas have been described by Rivière et al. [23,24] in studies investigating kinematic alignment of the hip and by Akiyama et al. [25]. Follow-up studies might aim to show clinical differences with large changes to AFA or investigate why FFR changes between preoperative and postoperative states.

Further exploring this idea of compensatory mechanisms occurring at the hip, the authors have noted that major adjustments to acetabular version from native, although protective for instability and edge-loading, can create gait disturbances despite no changes to the AFA. The belief is that the significant body of evidence that supports preoperative analysis of the hip-spine relationship [26-28] has led in some instances to dramatic increases in cup anteversion, leading to an uncoupling of the native combined version. Such a patient with significantly increased cup version, but restored anatomic AFA, may have altered gait biomechanics, walk with significant internal rotation due to kinematic disharmony, and present with resultant iliopsoas pain. There is evidence to support this in the study by Uemura et al. [22] who observed a mean change in standing FFR from preoperative to postoperative configurations of −9.8° (internal rotation). Further studies of preoperative to postoperative changes in acetabular anteversion, AFA, and FFR are needed to substantiate these beliefs. However, we believe that the concepts of FFR and FFA may help improve surgical prescriptions on both the acetabular and femoral sides.

It has long been recognized that, to achieve optimal alignment and impingement-free range of motion in THA, both the femoral and acetabular component orientations should be considered. As such, CA targets have been proposed [29-32]. Despite their utility, these zones rarely incorporate pelvic tilt and its impact on functional cup anteversion and, to the authors knowledge, have not been previously formulated to consider FFR, referencing only AFA. However, considering femoral anteversion only in relation to anatomic landmarks, as AFA does, could be seen as analogous to only considering the cup orientation in a supine AP radiograph, as it does not provide an understanding of the functional position of the prosthesis. It is now understood that both the pelvis and femur can rotate substantially between functional positions, altering the orientation of the components. Given the degree of variation observed in our study, CA targets may need to consider FFA instead of AFA, as we have noted that an additional 13% of patients would fall outside a widely cited CA zone when considering the functional alignment of the femur. Therefore, like the adoption of preoperative functional pelvic radiography to understand the patient's pelvic mobility [28,33], functional knee imaging should be considered to understand if a patient's functional CA is significantly different to their anatomic CA.

Our study has several limitations. First, we did not incorporate pelvic tilt values, and as such, the patients defined as being "at risk" due to their FFR from supine to standing may have had a favorable pelvic tilt change that would not place them at risk of impingement.

However, this was not seen as consequential as the aims of the paper were to define FFA, demonstrate its high variability across a large sample of patients requiring THA, and discuss its implications for femoral stem anteversion targets in THA. Second, we did not stratify or exclude patients based on the pathology. This meant our sample of patients included patients with primary and secondary osteoarthritis, where secondary osteoarthritis may have been associated with dysplasia, slipped capital femoral epiphysis, Perthes-Legg-Calves disease, or other conditions that can dramatically increase a patient's AFA. However, this improves the generalizability of the study as the purpose of the paper was to define the full range of FFA of all patients requiring THA, not specifically for patients with primary osteoarthritis. Third, it should be emphasized that our study contains only preoperative imaging data of patients with pathological hips. It has been shown that pelvic tilt changes from preoperative to postoperative states [34], with greater changes occurring in patients with a more anteriorly rotated pelvis. These larger changes are likely due to preoperative hip contractures resolving, which may be a mechanism to reduce pain that is secondary to the patient's arthritis. Therefore, similar phenomena may occur on the femoral side whereby patients excessively rotate their femurs externally or internally to reduce pain, and therefore, their postoperative FFR may naturally differ from their preoperative FFR. Further research into this is needed to understand which patients may undergo natural changes to their FFR from preoperative to postoperative states, and our results should be interpreted accordingly. Fourth, there is a degree of inapplicability to surgeons and patients who do not have access to the imaging requirements for the preoperative analysis discussed in our study. However, EOS (EOS Imaging, Paris, France) scans have been shown to accurately determine FFR [35] and present another option of measuring this parameter preoperatively, increasing its accessibility. Further research could also investigate how well FFR can be assessed from preoperative anteroposterior radiographs by using the lesser trochanters as a reference. Finally, our study did not address the extent to which AFA can be changed intraoperatively to achieve a desirable ASA and FSA. Previous studies have shown that a patient's unique femoral morphology dictates the achievable AFA when using metaphyseal-filling, press-fit components; however, this is more controllable in cemented or modular stems [16,36]. Therefore, when using an uncemented femoral component, it may not be feasible to alter FFA significantly. However, preoperative knowledge of a patient's unique femoral morphology using 3D templating can provide surgeons with the knowledge of the achievable femoral anteversion with different implant types.

Conclusions

In sum, functional alignment of the femur is understudied. We have demonstrated that the femur, like the pelvis, can rotate substantially between supine and standing positions, altering the functional orientation of the femur. These changes in FFR between positions may escalate the risk of prosthetic or bony impingement or may have downstream consequences on soft-tissue tensioning when dramatic alterations to femoral or acetabular anteversion are made intraoperatively. Therefore, like the hip-spine relationship, we believe the pelvis-femur relationship plays a significant role in patient outcomes, and further research into FFA/FFR may improve both acetabular and femoral component positioning.

Acknowledgment

The authors would like to acknowledge 360 Med Care for their support to this research.

Conflicts of interest

Dr. Brad Miles receives royalties from Corin; is a paid consultant for 360 Med Care; and has stock or stock options in 360 Med Care. Dr. J. Balakumar receives royalties from Medacta; is in speakers' bureau of or gave paid presentations for Medacta, Arthrex, and J&J; and is a paid consultant for Medacta and Stryker. Dr. J. Twiggs and M. Hardwick-Morris are paid employees of 360 Med Care. Dr. K. Kacker declares no potential conflicts of interest.

For full disclosure statements refer to https://doi.org/10.1016/j.artd.2022.09.002.

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