Idiopathic Rotational Abnormalities of the Lower Extremities in Children and Adults

Jordan A. Gruskay, MD

Austin T. Fragomen, MD

S. Robert Rozbruch, MD

Investigation performed at the Hospital for Special Surgery, New York, NY

Abstract

» Rotational malalignment of the lower extremity is a potential cause of hip, knee, and ankle pain.

» Physical examination must include observation of gait and an assessment of femoral rotation and the thigh-foot axis with the patient prone.

» Advanced imaging helps to quantify the degree of deformity, improving the accuracy of the preoperative plan.

» Surgical correction of rotational malalignment of the femur and tibia is reserved for severe, symptomatic deformity.

» Future software that allows for 3-dimensional assessment of alignment and preoperative planning will further aid in the correction of the complex deformities.

Idiopathic rotational abnormalities of the lower extremity have been studied for decades, yet there remains no consensus regarding the etiology of these conditions and at what degree of deformity a normal variant crosses the threshold into malalignment (known as "torsion"). In-toeing or out-toeing, the most conspicuous sign of torsional deformity, is first noticed in young children as an alteration of the foot progression angle[1,2]. It is generally believed that most rotational deformities in children resolve over time, making the treatment of childhood deformity controversial[3,4]. It is critical to recognize that compensatory rotation at the hip, knee, or foot may lead to apparent correction as seen by normalization of the foot progression angle despite persistent osseous abnormality and joint malposition[2,4-7]. Posttraumatic malunion is a separate but important etiology of rotational deformity. Meanwhile, deformity due to metabolic and neurological conditions must be considered during the initial work-up. Pathological rotational abnormality can cause difficulty with walking, patellofemoral pain, and instability and has been implicated in femoroacetabular impingement (FAI), patellofemoral arthritis, and knee and hip osteoarthritis in adults[8-16].

Natural History

An appreciation of the childhood rotational development pathway helps us to better understand associated deformity in adolescents and adults. Limb rotation starts in utero and is part of normal development. At 5 months, the normal fetus has about 20° of internal tibial torsion. At birth, many infants have internal tibial rotation (2° to 4°), increased femoral anteversion (~40°), and external contractures at the hip[3,10,17]. These uterine molding effects typically

Disclosure: No external funds were received in support of this study. On the **Disclosure of Potential Conflicts of Interest** forms, *which are provided with the online version of the article*, one or more of the authors checked "yes" to indicate that the author had a relevant financial relationship in the biomedical arena outside the submitted work (http://links.lww.com/JBJSREV/A407).

resolve spontaneously, after which abnormal rotation is revealed[3]. Rotational change continues until the age of 8 to 10 years, with the tibia externally rotating nearly 15° to 20° and the femur externally rotating 25° (thereby decreasing anteversion)[5,18,19]. There is certainly a packaging component to pathological limb rotation, as excess femoral anteversion that is present at birth often persists into skeletal maturity[20,21]. Meanwhile, rotation has been shown to vary based on laterality, indicating that torsion may develop or adapt over time[3,22,23]. Further evidence of the progressive development of torsion is seen in patients with concurrent deformity of the tibia and femur[5], such as compensatory external rotation of the tibia after the age of 8 years in patients with in-toeing gait secondary to femoral anteversion[4,21].

Clinical Evaluation

Evaluation begins with a thorough history and physical examination. Many benign rotational variations are seen in children and adults, and it is important to differentiate normal variability from pathological deformity. The clinical history should include an assessment of issues during pregnancy or birth and the meeting of developmental milestones. A family history of musculoskeletal disorders or hereditary conditions that may predispose to rotational malalignment (e.g., vitamin D-resistant rickets, mucopolysaccharidoses, achondroplasia, epiphyseal or metaphyseal dysplasia) should be included[24]. The extent of functional impairment experienced by the patient must be elicited.

Next, a detailed musculoskeletal examination is performed. The patient wears shorts in order to allow for improved visualization of alignment and function. The initial focus is on general appearance, including stature, posture, and signs of limb or spine asymmetry that may indicate a syndromic condition. The crux of the physical examination is the assessment of the rotational profile. Hip rotation can be assessed with the patient in either the supine or prone position. With the patient in the prone position, the hip is extended and the knee is flexed to 90°. The prone position is preferred as the pelvis can be better stabilized, goniometer measurement is easier, the extended hip more closely resembles the walking position, and comparison with the contralateral leg is easier[25,26]. In 1985, Staheli et al. evaluated 1,000 limbs in patients of all ages and determined normal values for rotational positioning and passive range of motion of the lower extremities that are still used today[3]. The measurements that they described (internal and external hip rotation, thigh-foot axis, transmalleolar axis, and foot progression angle during gait), combined with the heel-bisector angle, which assesses concurrent foot deformity, allow for determination of the existence and location of deformity prior to imaging. Increased levels of hip internal rotation are suggestive of femoral anteversion[27], whereas limited internal rotation may indicate decreased anteversion, retroversion, or femoroacetabular dysplasia[16]. However, range-of-motion values do not necessarily correlate with the degree of anteversion[27]. Increased femoral anteversion also may be diagnosed on the basis of medially-facing patellar alignment during gait or during standing with the feet pointed straight ahead ("winking patella sign"). The "W" sitting position is another characteristic sign of anteversion (Fig. 1). The "eggbeater" running pattern also may be seen during the gait examination secondary to internal rotation of the thighs during swing phase[24]. Although not a component of the rotational profile as described by Staheli et al., femoral anteversion can be assessed by determining the relative positions of the greater trochanter and the transverse axis of the femoral condyles[25,28], or it can be estimated as the midpoint of the passive rotation arc of the hip, but physical examination correlates poorly with computed tomography (CT) measurements[29,30].

Classically, the thigh-foot axis is used to assess tibial rotation. In reality, it is a composite measurement of a combination of tibial and hindfoot rotation in relation to the longitudinal axis of the thigh. Assessment is performed with the patient in the prone position, with the knee flexed to 90° and the ankle in a neutral position. A goniometer is used to measure the angular difference between the axis of the foot and the axis of the thigh. Infants have 5° of internal rotation on average. The thigh-foot axis externally rotates to about 10° by the age of 8 years, and there is little change from this point through adulthood[3,31]. External tibial rotation in infancy is less common and often worsens during growth, necessitating that these patients be closely followed as they may need surgery to prevent future patellofemoral issues[31]. Concurrent foot deformity can alter the measurement of the thigh-foot axis[3] and is evaluated with the heel-bisector line, which is drawn through the midline axis of the hindfoot. This line should pass through the second web space in a neutral foot, and medial or lateral deviation is a sign of forefoot adduction or abduction[32]. Metatarsus adductus, cavus, or clubfoot are potential causes of in-toeing, whereas pes planovalgus is a potential cause of out-toeing.

Finally, functional assessment of the extremity during gait is performed. The foot progression angle is defined as the angular difference between the axis of the foot and the line of progression (an imaginary straight line along which the patient walks). The foot progression angle is determined by the combination of femoral and tibial rotation, foot shape, and muscular forces and represents the global alignment of the lower extremity. By convention, in-toeing is considered a negative angle whereas out-toeing is positive. A typical in-office assessment is performed with the patient walking a straight line directly toward the examiner. The foot progression angle remains mildly positive (average, 6° to 10°) throughout growth, with relative out-toeing in young children (due to increased lateral rotation of the hip) and in elderly adults (due to progressive loss of hip internal rotation)[3,33,34].

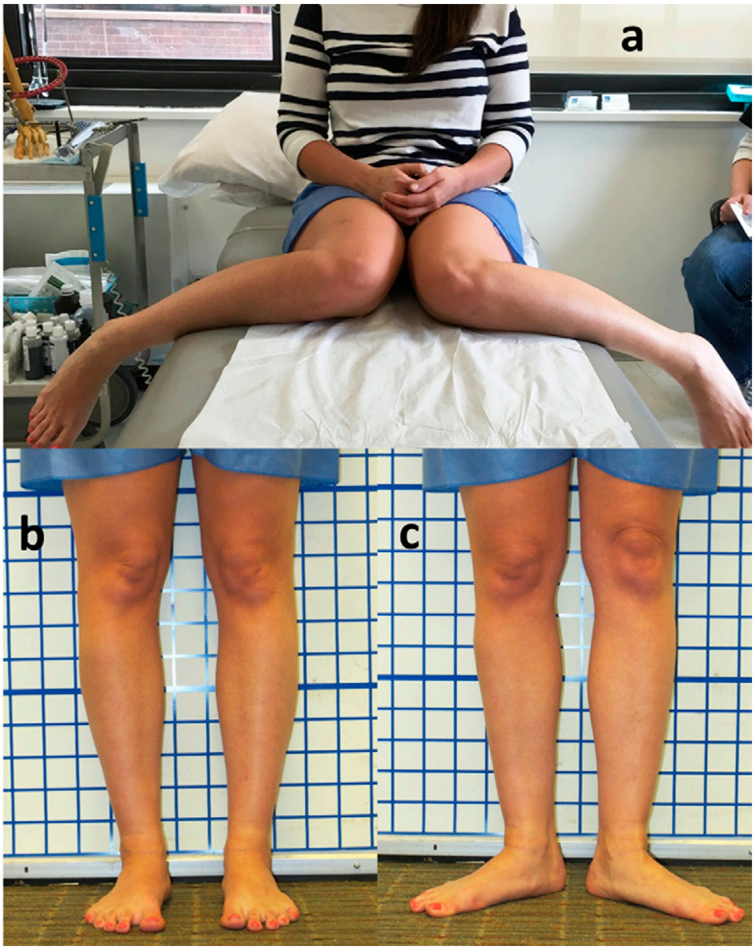

Fig. 1

Figs. 1-A, 1-B, and 1-C Photographs showing the physical examination findings typical of a patient with severe rotational deformity. **Fig. 1-A** The classic "W position" in a patient with severe femoral anteversion. **Fig. 1-B** The "winking patella sign" is seen with bilateral tibial torsion. **Fig. 1-C** Excessive foot external rotation is seen when the patellae are positioned facing forward.

It is important to be aware that the foot progression angle can be normal even in the setting of severe deformity. Several reports have described coupling of femoral anteversion and external tibial torsion, a compensatory adaptation that helps to normalize the foot progression angle[5,21,22,35-37]. Tibial torsion is intimately related to the foot progression angle and usually twists in the same direction, whereas the femur often rotates in the opposite direction[5]. Offsetting rotation can occur in >50% of patients, evidence that supports a full examination even for patients with an apparently normal gait and foot progression angle[5]. Gait analysis (mandatory for neurogenic patients) provides an objective overview of trunk, pelvis, hip and extremity rotation throughout the gait cycle and can assist in unmasking relationships between static osseous abnormalities and dynamic mechanisms of compensation at the hip and the knee[2,29].

With the advent of advanced imaging technologies, the value of a detailed physical examination has been questioned[25,27,28,38-42]. Although correlation between examination and imaging findings is often noted, there can be noteworthy and unpredictable differences in absolute value of degrees of rotation. Tamari et al. reported measurement errors of ~5° but noted overall good correlation between clinical and magnetic resonance imaging (MRI) findings, indicating the usefulness of physical examination in screening for disease[39]. Several investigators have compared goniometric and CT measurements and have concluded that the 3° to 5° measurement error was acceptable in clinical practice[38,43]. Meanwhile, others have noted significant differences between clinical and CT assessment of femoral anteversion and tibial torsion, and this discordance between radiographic and examination measurement increases as rotational deformity worsens[29,42]. Theoretically, these unpredictable results may be secondary to soft-tissue or acetabular restraints that are not accounted for in many imaging studies.

Ultimately, a provider who can perform a thorough assessment of the rotational profile and has good understanding of expected normal values for each site at each age should be able to accurately diagnose torsional deformity even without the assistance of radiographic studies.

Radiographic Evaluation

For patients with abnormal findings on physical examination, radiographs are made to assess the affected joints. Hip and pelvic radiographs can identify acetabular or femoral dysplasia and early osteoarthritis. Anteroposterior, lateral, and Merchant radiographs of the knee can identify patellofemoral alignment issues and arthritis. Rotational deformity about the knee or ankle may present with increased tibia-fibula overlap (Fig. 2). For patients with severe in-toeing or out-toeing, radiographs of the foot can also be useful for identifying metatarsus adductus and quantifying pes planus. Finally, a standing lower extremity radiograph or EOS imaging (a biplanar low-dose imaging system) should be used to assess concurrent coronal plane deformity and limb-length discrepancy[44], but surgeons must be aware that coexisting tibial torsion deformity may confound the assessment of knee malalignment[45-47]. Patients with external tibial torsion and genu varum often will appear to have more varus when the feet are pointing forward. Patients with femoral anteversion will appear to have a high femoral neck-shaft angle that will decrease after correction.

Unfortunately, rotational alignment is difficult to assess on radiographs. Several authors have described methods for determining femoral anteversion with use of axial or biplanar radiography[48-51], with questionable accuracy and reproducibility[25,50,52,53]. Meanwhile, radiographic methods for determining tibial torsion provide values that are similar to physical examination measurements but not CT comparisons[54,55]. Currently, we use radiographs to assess coronal and sagittal alignment as well as joint integrity. Other imaging modalities that allow for more quantitative assessment, such as ultrasound[56-58], fluoroscopy[23], and MRI[27,59,60], have been described.

Rotational profiling with use of 3-dimensional (3D) imaging such as MRI and CT is the definitive method for the diagnosis of lower extremity abnormality. Measurements are taken from 2D axial slices through the femoral neck, distal part of the femur, proximal part of the tibia, and ankle mortise to determine rotation. Axial imaging theoretically provides highly accurate and repeatable measurements, but it is not without limitations. The orientation of the axial cut can change planes, which has been shown to alter measurement results. The most widely used femoral measurements rely on CT-derived axial slices through the femoral neck and distal femoral condyles. With all techniques, the distal

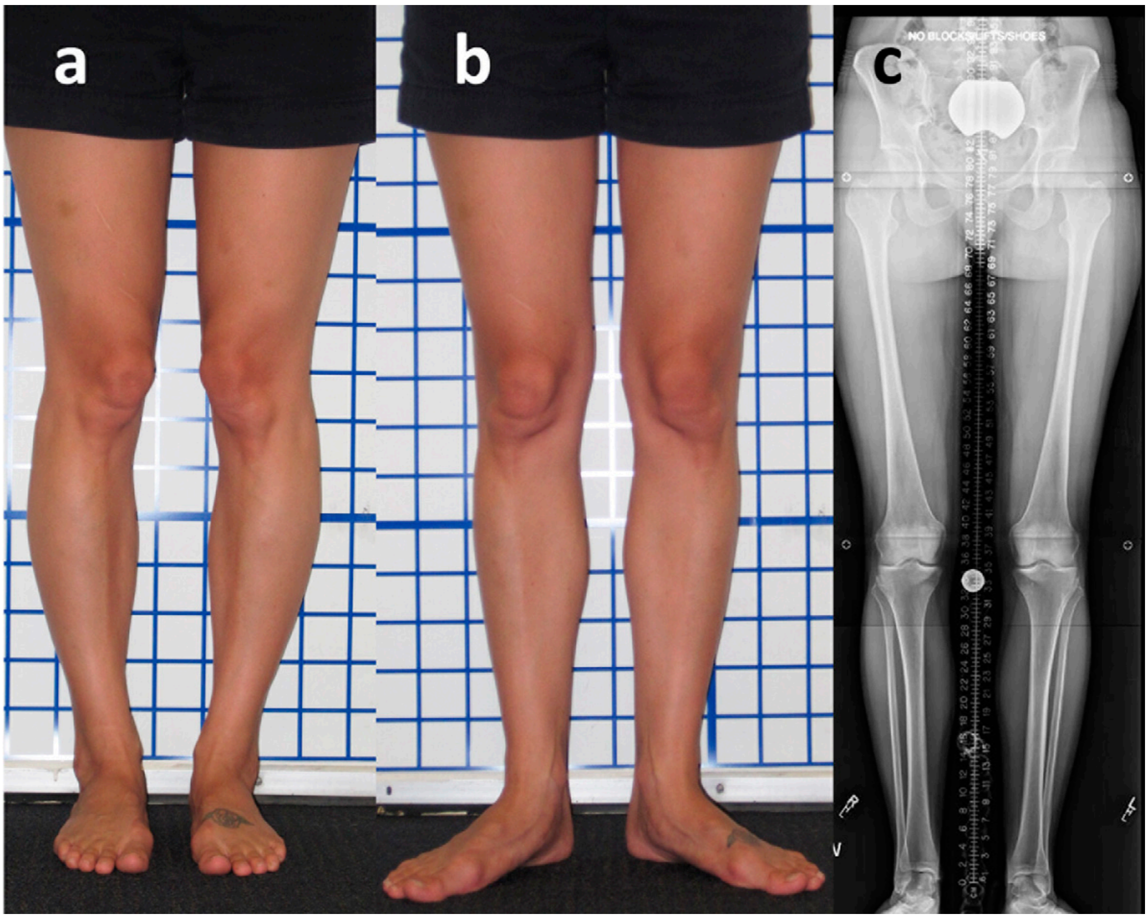

Fig. 2

Figs. 2-A and 2-B Photographs showing the lower limbs of a patient with severe rotational deformity about the tibia. **Fig. 2-C** Anteroposterior long-cassette standing radiograph showing classic lateral tibia-fibula overlap.

TABLE I Composite Normative Values of Rotation of Lower Extremities as Measured with CT

Author	No.	Age* *(yr)*	Femoral Anteversion†	Tibial Torsion†	Measurement Method: Femur	Measurement Method: Tibia	Comments
Botser et al.[27]	129	36 (14-74)	15.9°	—	Femoral neck axis on oblique slice to tangent of the posterior aspect of femoral condyles	—	Statistically significant discrepancies found in anteversion angle measurements between MRI and CT scan
Decker et al.[68]	211	34 (0-105)	18.2° ± 9.9°	—	Femoral neck axis to tangent of the posterior aspect of femoral condyles	—	Statistically significant discrepancies found in anteversion angle measurements between MRI and CT scan
Erkocak et al.[12]	40	20-40	11.6° ± 3.5°	26.0° ± 4.2°	Line drawn parallel to femoral neck to line tangent to posterior border of femoral condyles	Line tangent to posterior border of proximal part of tibia to intermalleolar line at level of ankle joint	
Jakob et al.[76]	45	Cadaveric tibiae	—	30°	—	Axis through widest transverse condylar diameter to line bisecting anteroposterior diameter of distal part of tibia that passes through anterior part of fibula at level of incisura	Maximum amount of tibial torsion occurs in proximal tibial metaphysis
Keppler et al.[67]	78	2-18	34° at 5 yr; 19° at 17 yr	32°	—	—	No correlation of tibial torsion with age. Statistically significant side-to-side torsional differences noted.
Koerner et al.[70]	328	Not reported	8.8° ± 9.7°	—	Axis of femoral neck to the posterior femoral condylar line	—	Trend but no significant differences based on sex or ethnicity. Retroversion common in white (21.4%) versus Hispanic (7.1%)
Kuo et al.[52]	10	20-64	12.4° ± 3.8°	—	Line connecting center of femoral head with center of neck to line parallel to posterior femoral condylar line, just distal to upper pole of patella (Hernandez method)	—	Close correlation between anatomical cadaver measurement and CT value
Reikerås and Høiseth[73]	50	Adult	—	Female: 32.3° ± 8.3° (R), 30.7° ± 10.4° (L); Male: 35.3° ± 7.6° (R), 34.0° ± 10.3° (L)	—	Dorsal tangent of tibial condyle to malleolar bisector line at ankle joint	Statistically significant differences (up to 9°) between rotation of consecutive proximal tibial axial slices

continued

TABLE I (continued)

Author	No.	Age* (yr)	Femoral Anteversion†	Tibial Torsion†	Measurement Method: Femur	Measurement Method: Tibia	Comments
Seber et al.[69]	50	Adult males	6.5° ± 7.7° (R); 5.8° ± 8.4° (L)	30.9° ± 7.1° (R); 29.1° ± 6.9° (L)	Line connecting center of femoral head with center of femoral neck to dorsal tangent of femoral condyles (Hernandez method)	Proximally, with the axial cut taken at the level of the fibular head, a line connecting the junction of anterior and lateral fibular margins with the most prominent part of the medial tibia to intermalleolar line distally at level of incisura fibularis	Average foot progression angle of 13.7°
Strecker et al.[22]	355	Adult	24.1° ± 17.4°	34.9° ± 15.9°	Line connecting center of femoral head with center of greater trochanter to dorsal condylar line	Dorsal tangent of tibial plateau to line connecting center of an ellipse formed from surface of medial malleolus and another ellipse formed by incisura fibularis (Ulm method)	Tibial torsion R > L ($p < 0.001$)
Stuberg et al.[38]	17	12.3 (3.3-24)	—	24.5° ± 8.4°	—	Tibial condyle bisector line to malleolar bisector line at incisura	
Waidelich et al.[63]	50	31 (13-61)	33.1° ± 8°	20.4° ± 9°	—	—	Statistically significant side-to-side differences (4.3° in femur, 6.1° in tibia)

*The values are given as the mean and/or the range, when available. †The values are given as the mean with or without the standard deviation, when available.

axis of the femur is a line tangent to the posterior aspects of the condyles on the axial image, where the condyles have the largest anterior-to-posterior distance[18,61,62]. Measurement of the femoral neck axis is variable and can be performed with use of different 2D slices (axial, oblique, superimposed) and anatomical landmarks (femoral head, femoral neck, greater trochanter)[19,22,61,63-65]. The use of 3D-CT reconstructions has also been described[66]. CT offers the ability to measure acetabular version. If the femoral version that was measured during the physical examination does not correlate with that measured on CT scans, then the acetabular version needs to be evaluated as acetabular retroversion can decrease the measurement of internal rotation during physical examination[43].

A wide range of normative CT values for femoral anteversion have been reported (from 6° to 24°) (Table I)[12,22,27,52,63,67-71]. Differing measurement techniques are largely responsible, with mean values differing by as much as 11.4° (range, 11° to 22.4°) for the same patients when measured with different techniques[18]. Even when the same technique has been used, values have been shown to be highly dependent on the CT slice, leading to intraobserver and interobserver differences of as much as 15°[52,72-74]. Age, sex, ethnicity, and laterality may contribute to the variability of reported values[22,63,68,70,75].

Jakob et al. first described the use of CT scanning for the evaluation of tibial torsion in 1980[76]. Other techniques have been described since then. Proximally, the axis may be drawn either (1) parallel to the posterior parts of the tibial condyles[59], (2) tangential to the posterior rim of the tibial plateau[12,29,62], or (3) as an axis line bisecting the widest anteroposterior diameter of the medial and lateral tibial condyles[38,77]. The level of the proximal tibial slice may be hard to define, and, given that the majority of tibial torsion occurs in the proximal 4 cm of the tibia, slices must be chosen as proximal to the tibial plateau as possible[15,71].

A number of other measurement techniques have been described to define the distal tibial axis[22,74]. The bimalleolar method describes a line drawn from the center of the anteroposterior diameters of the medial malleolus and fibula in an axial slice either just proximal to the ankle mortise with the fibula in the incisura[29] or at the level of the talar dome[12,38,62,73]. The posterior intermalleolar line at the level of the talar dome also has been used[59]. Variability has been noted with these reference points, with average disagreement of as much as 13° on intermethod comparisons[74].

As in the femur, a wide range of normative CT values for tibial torsion (from 24.5° to 38°) have been reported in the literature[12,22,36,38,63,67,69,71,73,76] (Table I). Possible explanations include sex, race (with Asian and African American individuals having lower values), laterality, hip dysplasia, and the

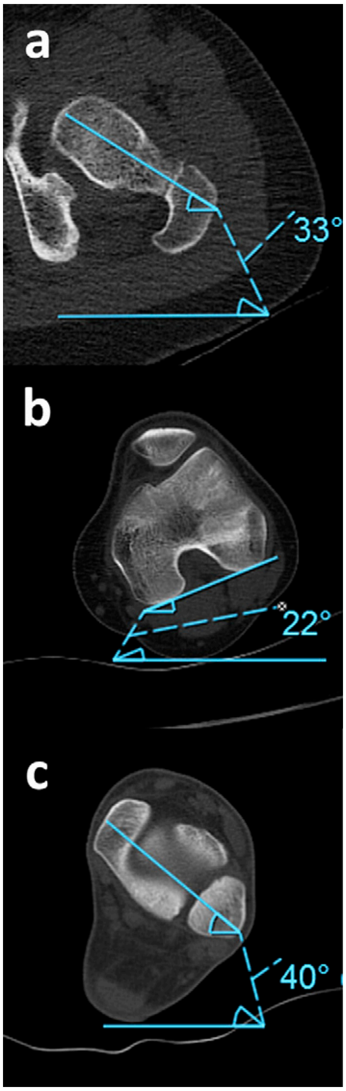

Fig. 3

Figs. 3-A, 3-B, and 3-C Representative CT slices for a 14-year-old girl with pathological femoral anteversion and external tibial torsion. By convention, external rotation is defined as positive and internal rotation is negative. In this example, the distal femoral axis is used as a proxy for the proximal tibial axis when determining tibial rotation. Femoral anteversion is equal to the proximal femoral axis angle minus the distal femoral axis angle. Tibial external rotation is equal to the distal tibial axis angle minus the distal femoral axis angle. With this method, femoral anteversion in this patient is measured as 55° and tibial external torsion is measured as 62°. **Fig. 3-A** To define the proximal femoral axis, a CT slice capturing the femoral head and neck is chosen. A line bisecting the femoral neck to the center of the femoral head is drawn, and the angle as compared with a horizontal line is captured. **Fig. 3-B** The distal femoral axis, defined as a line tangent to the most posterior aspect of the femoral condyles, is drawn on the CT slice where the condyles are most prominent. **Fig. 3-C** The distal tibial axis is defined as the malleolar bisector line at the level of the ankle joint.

presence of secondary arthritis[36,37,73]. Meanwhile, the anatomy of the posterior tibial condyles has been noted to be quite variable, with as much as a 10° difference in angulation depending on the axial slice chosen[73]. For this reason, some have advocated measuring the torsion of the "leg" from the femoral condyle (which has only 1° to 2° of variability) to the distal tibial reference point[73] (Fig. 3).

With the widespread use of CT for the evaluation of the rotational profile, concerns remain regarding the radiation exposure in young patients[78-80]. In practice, the use of CT also may be limited in younger patients because of incomplete ossification. Physicians regularly using CT should consider developing protocols that reduce risks due to ionizing radiation for their younger patients. Alternatively, EOS (the biplanar low-dose imaging system) has been used for 3D modeling of the lower extremity and measurement of femoral and tibial rotation[62,81,82]. EOS imaging requires radiation doses lower than even conventional radiographs, and computer software reconstructions allow for measurements of rotation[62,83].

MRI methods are considered relatively accurate and do not subject the patient to any radiation, but tests are time-consuming and costly compared with CT scanning[59,84]. Koenig et al. described an MRI protocol for assessing rotation within approximately 10 minutes; this protocol may be important when assessing children, for whom sedation may be required for adequate imaging[59]. Additionally, MRI measurements have been found to vary by as much as 5° depending on the imaging protocol[85], are systematically biased toward lower values ($\leq 10°$), and are less accurate than CT measurements[27,54,60,62,75]. Discrepancies noted throughout multiple imaging studies likely represent the difficulty of creating a 2D measurement projection of what is really a 3D problem. Additionally, deformity can occur at different locations along the femur, such as supratrochanteric deformity, which is measured as the tilt of the femoral neck, and infratrochanteric deformity, which is measured as the rotation of the femoral shaft[86]. Methods to quantify femoral rotation with use of 3 axes for measurement or 3D-CT volumetric reconstructions have been described and are believed to more accurately localize transverse plane rotation than conventional methods[42,86].

Sequelae of Rotational Deformity

Different conditions associated with rotational deformity present at different stages of life and may include abnormal gait, patellar instability and pain, slipped capital femoral epiphysis (SCFE), hip labral tears, FAI, and osteoarthritis of the knee and the hip.

Issues with the extensor mechanism include patellofemoral pain, malalignment, and instability[9,12,14,28,87]. The term *miserable malalignment* describes a combination of femoral anteversion, tibial external torsion, and an increased Q angle, which can occur alongside patella alta, squinting patella, genu varum, and genu recurvatum[12,88-90]. While coronal plane deformity clearly plays a role in altering the Q angle, axial plane changes also affect tracking biomechanics. Increased femoral anteversion displaces the patella medially, increasing the Q angle and altering the lateral patellar tilt angle[28,87,91], which drastically increases lateral patellofemoral contact pressures[92]. External tibial torsion displaces the tibial tubercle laterally, also increasing the Q angle[90]. Erkocak et al. demonstrated a close relationship between the Q angle, femoral anteversion, external tibial torsion, and anterior knee pain in adults 20 to 40 years of age[12].

While obesity is the primary risk factor for SCFE, it has been suggested that anatomical alterations of the proximal part of the femur may also put patients at risk for SCFE[93]. Meanwhile, excessive femoral rotation has been identified as a possible precipitator of FAI[16,27,94,95]. Botser et al. demonstrated that patients with low anteversion are more likely to have pincer

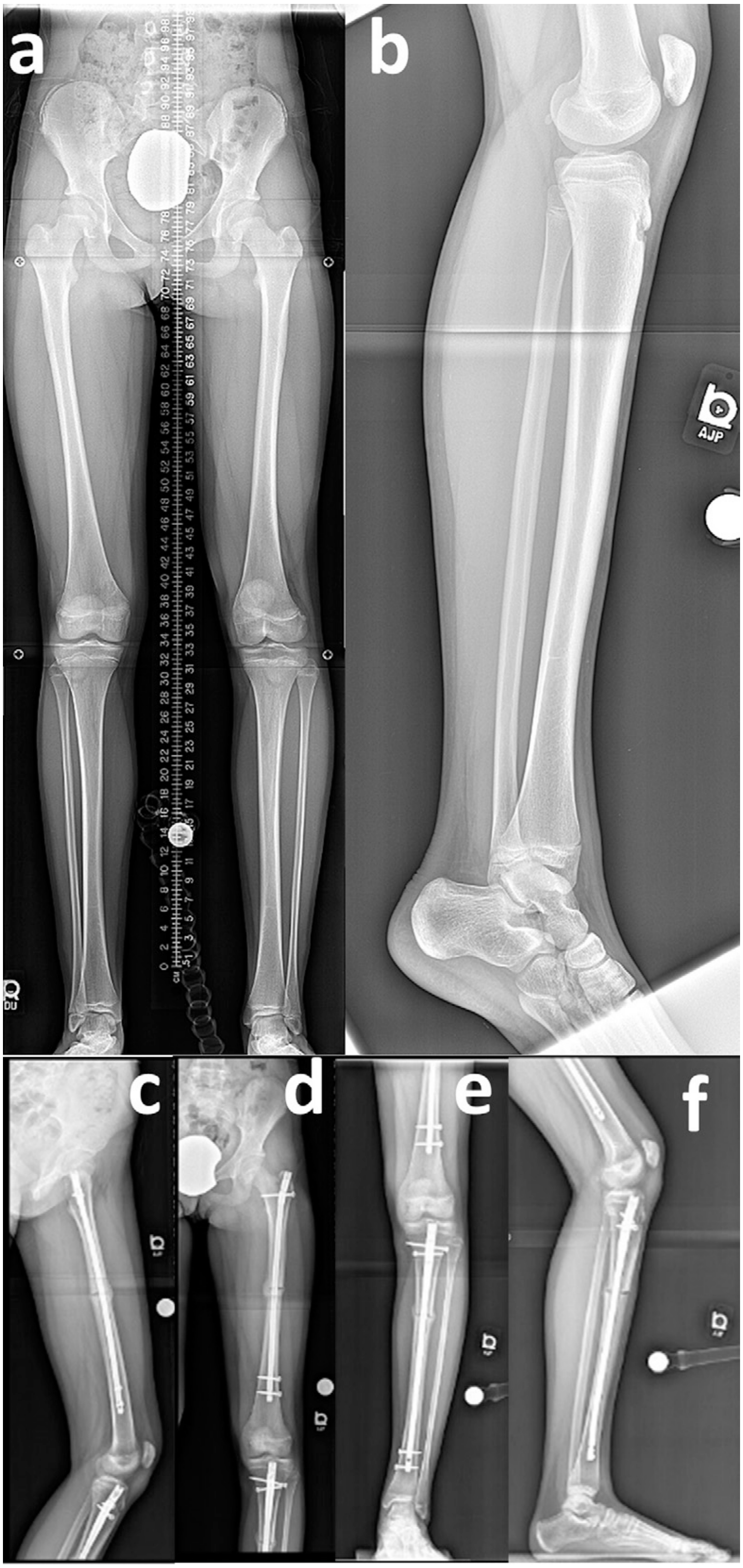

Fig. 4

Figs. 4-A through 4-F A 14-year-old girl with anteromedial left knee pain with pathological femoral anteversion (42°) and tibial external torsion (41°). The patient was 4 years post-menarchal, and the growth plates were nearly fused on CT imaging. Physical examination findings included 85° of internal rotation of the hip (compared with 65° on the contralateral side) and a 35° thigh-foot axis (compared with 15° on the contralateral side). The patient underwent concurrent left-sided femoral and tibial percutaneous osteotomies and nailing through greater trochanteric and transtendinous starting points, respectively. The femur was externally rotated by 25°. The tibia was internally rotated by 20°, and a fibular osteotomy was not needed. **Fig. 4-A and 4-B** Preoperative anteroposterior and lateral radiographs demonstrating classic radiographic findings of tibial torsion. The top left panel (**Fig 4-A**) shows an anteroposterior view of the knee joint, with an oblique view at the knee. The top right panel (**Fig 4-B**) shows a lateral view of the knee, with an oblique view of the ankle. **Figs. 4-C through 4-F** Radiographs made at 6 weeks postoperatively, showing healing and improvement of radiographic positioning.

impingement, whereas patients with high anteversion are more likely to have a cam deformity[27].

The longer-term sequelae of rotational deformity are not well understood. FAI is known to accelerate the progression of hip degeneration[94,95]. Terjesen et al. and Halpern et al. noted that femoral anteversion is a predisposing factor for hip

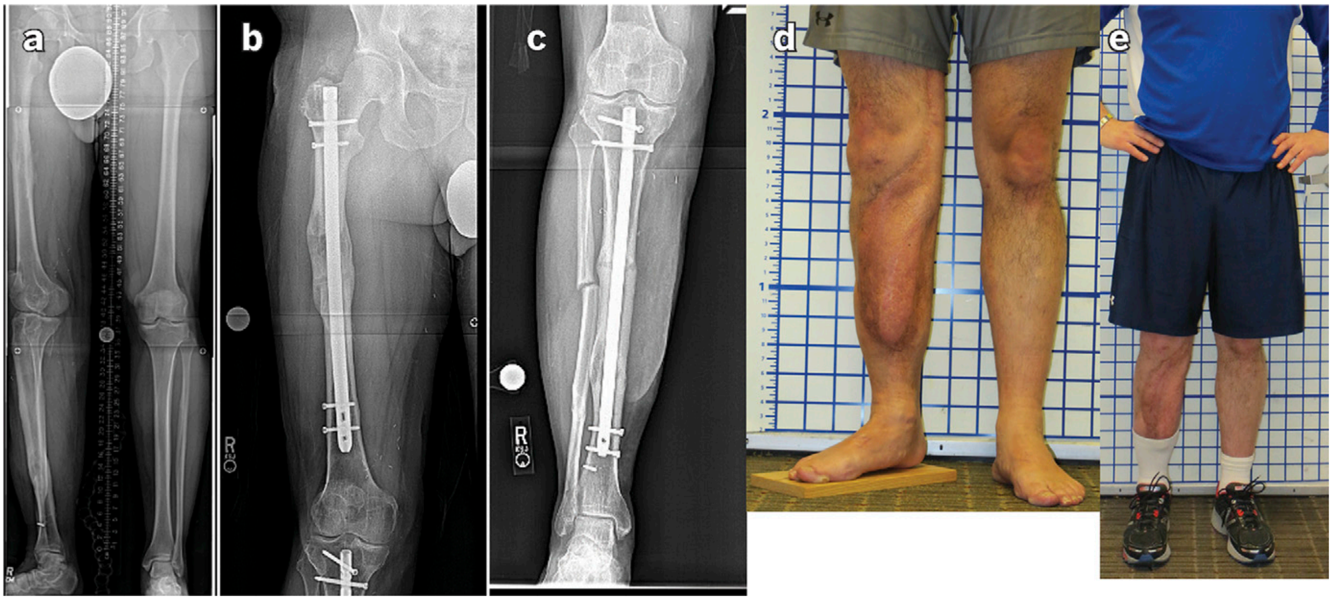

Fig. 5

Figs. 5-A through 5-E A 41-year-old man with posttraumatic rotational deformity of the right lower extremity following fractures of both the tibia and the femur. The femoral deformity was corrected in 2 stages with a piriformis entry nail. The second stage included concurrent tibial-fibular external rotation osteotomy and intramedullary nail fixation. **Figs. 5-A** Preoperative standing anteroposterior radiograph demonstrating a severe (60°) external rotation deformity of the femur and a 25° internal rotation deformity of the tibia. **Figs. 5-B and 5-C** Anteroposterior radiographs of the right femur and tibia, made 12 weeks postoperatively, showing improved alignment and interval bridging bone. **Fig. 5-D** Preoperative clinical photograph showing severe leg-length discrepancy and external rotation of the right lower extremity. **Fig. 5-E** Postoperative clinical photograph, showing correction of the foot progression angle and restoration of leg length discrepancy.

osteoarthritis[96,97]. Tönnis and Heinecke described a relationship between extreme values of anteversion and retroversion and increasing hip pain suggestive of early osteoarthritis[98]. Those authors recommended corrective treatment of excessive femoral version in order to decrease pain and decrease risk of early arthritis. Several other studies involving radiography, CT evaluation, and cadaveric specimens have demonstrated no association[37,99,100].

While investigations of the link between rotational malalignment and knee osteoarthritis have demonstrated inconsistent findings[98], pathological rotation is thought to increase shear forces across articular cartilage, leading to biomechanical changes in the subchondral bone and deep chondral layers[10,14]. Femoral anteversion is increased in patients with patellofemoral arthritis, a sign that excessive femoral torsion may contribute to increased wear of the patellofemoral joint[91]. Femoral retroversion is more likely to be associated with tibiofemoral osteoarthritis[11], and internal tibial torsion has been correlated with medial knee osteoarthritis[14,15,91,101-104].

Operative Considerations

Operative correction of torsional deformity remains a controversial topic, and the majority of published data are found in the pediatric literature, with poor application to adult populations.

Adults who present with torsion have self-identified problems related to malalignment and may benefit from osteotomy. As there is no absolute value of deformity that requires surgery, asymptomatic children who are brought in by concerned parents require a careful approach and may be best served by observation until symptoms appear.

Spontaneous remodeling of the femur with improvement of gait abnormalities occurs in most children by the age of 8 years, with little change after that point[3,105]. Unfortunately, nonoperative treatment for symptomatic femoral anteversion is ineffective[21,105]. Relative indications for surgery include hip, knee, or ankle pain in the presence of excessive anteversion or retroversion and/or functional concerns of persistent in-toeing, impaired gait, and tripping during athletic activity[106].

A number of osteotomy locations and fixation methods have been described[105,107-111]. Percutaneous osteotomies involve minimal periosteal stripping and are thought to improve the speed and success of osseous union. This technique is particularly important in adults with less-robust periosteum and decreased healing potential. Closed osteotomy with an intramedullary saw also has been described[112]. Plate fixation with either proximal or distal osteotomy is a well-described and effective technique, although serious complications are not uncommon (with a reported rate of approximately 15%)[113]. With the advent of a lateral trochanteric entry nail, intramedullary fixation is the preferred method for the correction of primary rotational deformities in older children[106,110,111]. The advantages of intramedullary nails include improved aesthetics, minimal soft-tissue dissection, early weight-bearing, load-sharing (which promotes osseous healing), and a

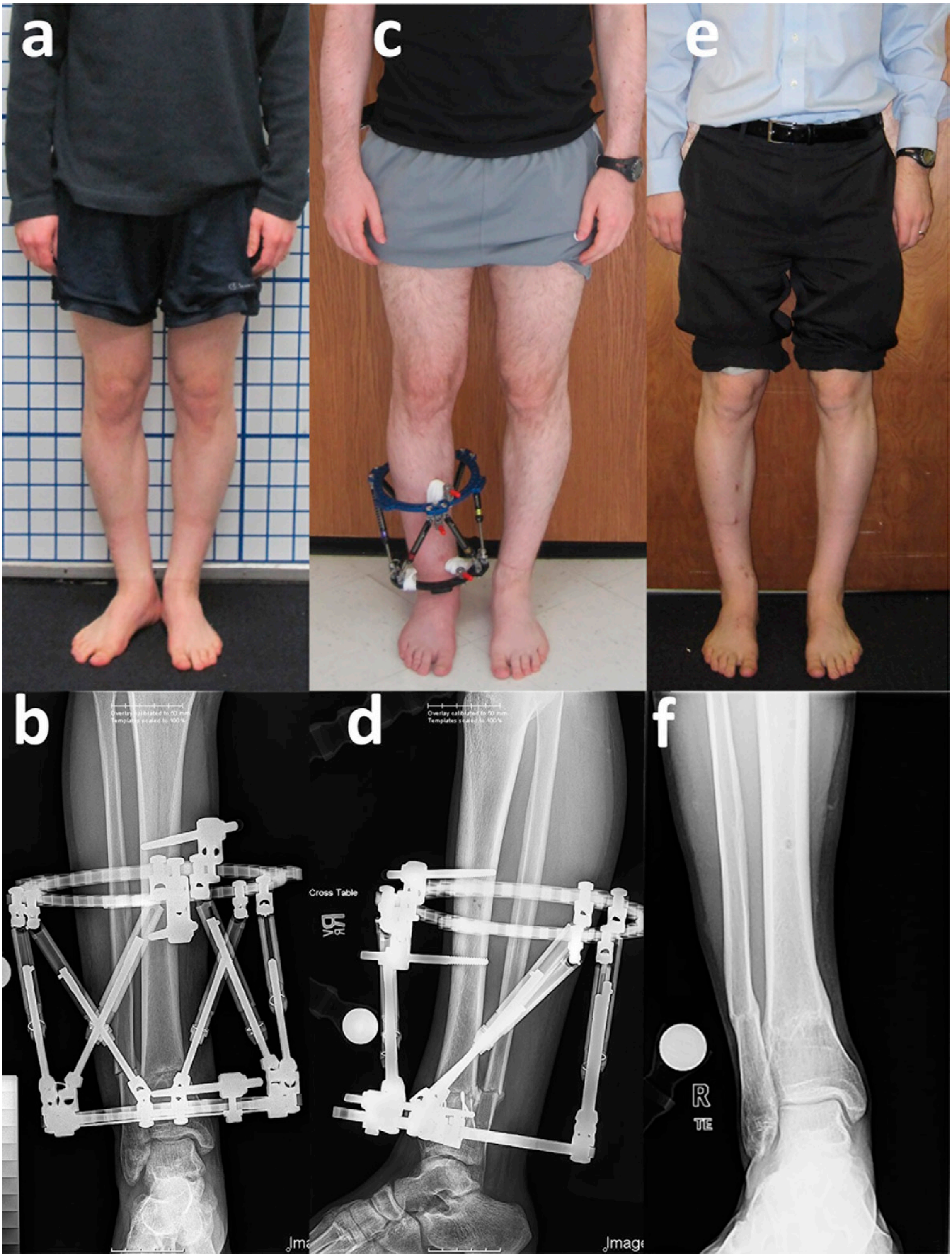

Fig. 6

Figs. 6-A through 6-F A 32-year-old man who presented with right knee pain caused by external tibial torsion of 57° (15° greater than that on the contralateral side). The patient underwent right tibial supramalleolar osteotomy and fibular osteotomy with application of a Taylor Spatial Frame. He gradually underwent correction of 15° starting on the third postoperative day, with daily adjustments for 15 days. **Fig. 6-A** Preoperative clinical photograph showing an obvious external foot progression angle. **Figs. 6-B, 6-C, and 6-D** Anteroposterior radiograph (**Fig. 6-B**), clinical photograph (**Fig. 6-C**), and lateral radiograph (**Fig. 6-D**) of the right lower leg, made 6 weeks after Taylor Spatial Frame correction. **Figs. 6-E and 6-F** Clinical photograph and radiograph, made 6 months postoperatively, demonstrating improvement of the foot progression angle and healing of the supramalleolar osteotomy site.

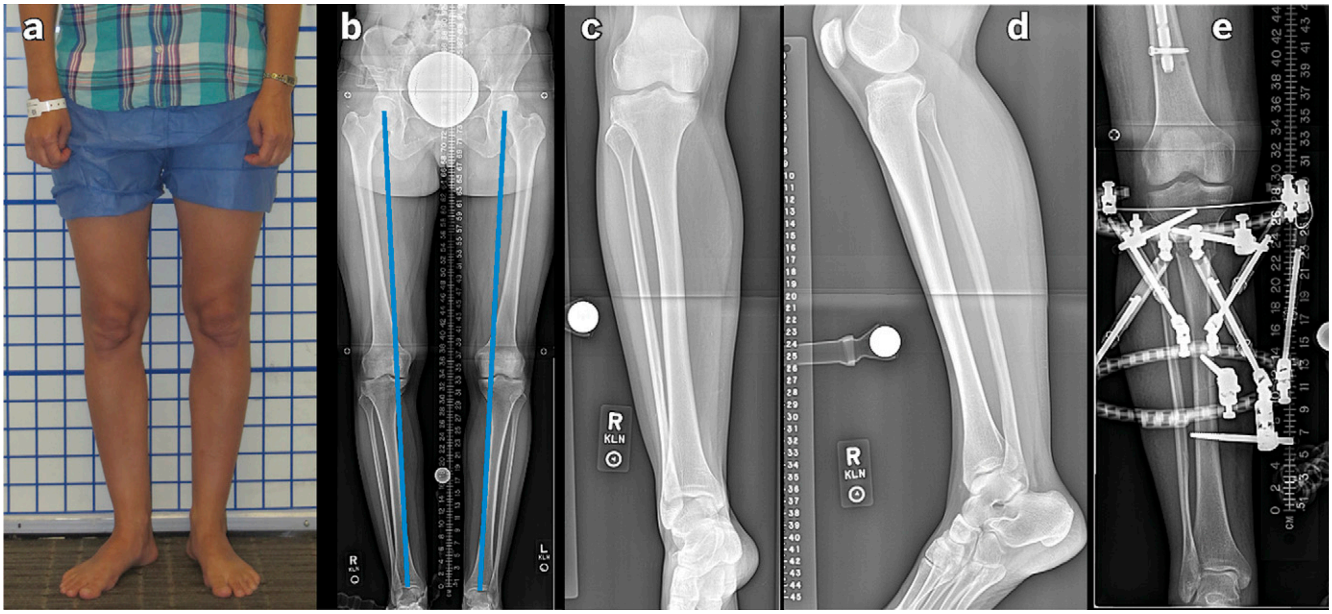

Fig. 7

Figs. 7-A through 7-E A 42-year-old woman with a history of genu varum presented with bilateral hip, knee, and ankle pain, all of which were greater on the right side than on the left side. CT scans showed 55° external tibial torsion and 33° femoral anteversion on the right side. The patient underwent derotation osteotomy and nailing of the right femur, proximal tibial osteotomy, and application of a Taylor Spatial Frame. Daily frame adjustments allowed for gradual correction of 25° rotation and 7° varus over 25 days. **Fig. 7-A** Photograph made with the patient standing with the right foot externally rotated 30°. The thigh-foot axis is 30° on the right and 15° on the left. **Fig. 7-B** Preoperative standing long-leg anteroposterior radiograph demonstrating bilateral varus deformity of the lower extremities. **Figs. 7-C and 7-D** Preoperative anteroposterior and lateral radiographs of the right leg, with obliquity of the ankle joint, characteristic of tibial torsion. **Fig. 7-E** Anteroposterior radiograph of the right leg, made 6 weeks postoperatively, demonstrating improved rotation of the leg as indicated by improved orientation of the ankle mortise.

decreased risk of complications. The reported complication rates have been low[106,110-112]. For younger patients, the nail can be placed safely through a trochanteric starting point[114,115] (Fig. 4), whereas for older patients, a piriformis starting point can be used[116,117] (Fig. 5). In order to avoid creating a varus deformity, care should be taken to select the correct nail size and starting point (which should not be too lateral)[118]. Fat embolism syndrome is a theoretical risk associated with intramedullary fixation, and vent holes drilled at the osteotomy site prior to reaming may reduce the risk of fat embolus. Percutaneous osteotomy and fixation with use of a modified Ilizarov frame has been described with excellent results, although the frame is poorly tolerated in the thigh[109]. The advantages of external frame application include the ability to bear weight immediately and to adjust alignment parameters postoperatively[119].

With regard to tibial torsion, surgery generally been avoided for patients younger than 8 years of age[3,105,120,121]. The indications for the treatment of idiopathic torsion remain vague and include the presence of severe deformity ≥3 standard deviations from the mean, but functional pain and disability remain the primary considerations[105,122]. Osteotomy for the treatment of tibial torsion can restore kinetic and kinematic parameters of knee motion to near-normal values[123]. Osteotomy is performed proximally, distally, or in the midshaft and can be either percutaneous or open. Fixation can be performed with an intramedullary nail, staples, casting, plates, Kirschner wires, or an external fixator[90,119,122,124-129]. Fibular osteotomy may be performed if the tibia derotation angle is >30°[122]. It is thought that an intact fibula could lead to incongruity of the ankle joint and may contribute to recurrence of deformity[124], although one study demonstrated that an intact fibula prevented the loss of fixation and angulation at the osteotomy site[126]. With regard to the level of osteotomy, proximal osteotomies are associated with a higher risk of complications, including peroneal nerve injury and compartment syndrome, but they are useful in patients with concurrent coronal knee deformity[90,125]. Casting in children requires no metal implants but includes the risk of loss of correction[126,127]. Plate fixation requires larger incisions, requires ultimate removal of the implant, may lead to a decreased rate of union because of the presence of rigid fixation, and is associated with increased rates of complications as compared with percutaneous pin fixation in distal tibial osteotomy[128]. Circular external fixation can be used to safely and reliably correct malalignment as the lower leg tolerates external fixation relatively well[130] (Fig. 6). Gradual correction makes neurovascular accommodation possible and compartment syndrome highly unlikely. External tibial torsion exists in as many as 50% of patients with congenital genu varum, whereas internal tibial torsion is often seen in patients with Blount disease[131-133]. The treatment of complex deformity with gradual correction with use of multiplanar fixation has yielded excellent results[131,132,134] (Fig. 7). Finally, the use of intramedullary fixation in the tibia has similar advantages as in the femur[90,129] and avoids risk of pin-site infection, but that method is reserved for skeletally mature patients, may require implant removal, requires acute correction (which may increase the risk of neurovascular complications), and can be associated with anterior knee pain (which is often an indication for the procedure in the first place)[129] (Fig. 4). Adjunctive procedures, including peroneal nerve release and prophylactic percutaneous fasciotomy, should be considered with large angular corrections. Overall, the reported complication rate for tibial osteotomies has ranged from 0% to 43%, with a 5% to 10% rate of major adverse events regardless of fixation method[129].

Miserable malalignment syndrome is best treated with concurrent ipsilateral rotational osteotomies and either intramedullary nailing or plate fixation[90]. Extensor mechanism realignment alone has a high rate of failure when the underlying cause of patellofemoral pain is either tibial or femoral rotation[135].

Limb-length inequality can be addressed at the time of osteotomy by gradually distracting the cut bone ends with use of either an internal lengthening nail or an external fixator[136].

Unfortunately, few studies have evaluated the long-term results of derotation procedures. Bruce and Stevens reported complete resolution of anterior knee pain in 27 extremities at 5 years of follow-up in a study of patients undergoing femoral and tibial derotation procedures for the treatment of miserable malalignment[90]. Meister and James reported similar findings at 10 years of follow-up[137]. Stevens et al. evaluated 16 subjects and reported persistent patellar instability at 5 years after surgery in 43% of patients who had undergone torsional correction following previously failed procedures for the treatment of anterior knee pain and patellar maltracking[138]. Stotts and Stevens, in a study of 59 patients who were managed with tibial derotation osteotomy with intramedullary nail fixation, reported that 23.7% of the patients had persistent knee complaints 2 years postoperatively[129]. Svenningsen et al. followed 52 children for 9 years following femoral derotation osteotomies for in-toeing, with only 2 patients reporting recurrence[107].

Overview

Rotational malalignment of the lower extremities is an important cause of hip, knee, and ankle pain. Understanding common presentation and physical examination findings is the first step to diagnosis, and advanced 3D imaging can aid in diagnosis and preoperative planning. Surgical intervention is uncommon, but it can be advantageous in the right patients with symptomatic deformity.

Jordan A. Gruskay, MD[1],
Austin T. Fragomen, MD[1],
S. Robert Rozbruch, MD[1]

[1]Hospital for Special Surgery,
New York, NY

E-mail address for S.R. Rozbruch:
rozbruchsr@hss.edu

ORCID iD for J.A. Gruskay:
0000-0003-3705-8997
ORCID iD for A.T. Fragomen:
0000-0002-9031-9079
ORCID iD for S.R. Rozbruch:
0000-0003-1632-4600

References

1. Kim HD, Lee DS, Eom MJ, Hwang JS, Han NM, Jo GY. Relationship between physical examinations and two-dimensional computed tomographic findings in children with intoeing gait. Ann Rehabil Med. 2011 Aug;35(4):491-8. Epub 2011 Aug 31.

2. Radler C, Kranzl A, Manner HM, Höglinger M, Ganger R, Grill F. Torsional profile versus gait analysis: consistency between the anatomic torsion and the resulting gait pattern in patients with rotational malalignment of the lower extremity. Gait Posture. 2010 Jul;32(3):405-10. Epub 2010 Jul 22.

3. Staheli LT, Corbett M, Wyss C, King H. Lower-extremity rotational problems in children. Normal values to guide management. J Bone Joint Surg Am. 1985 Jan;67(1):39-47.

4. Fabry G, Cheng LX, Molenaers G. Normal and abnormal torsional development in children. Clin Orthop Relat Res. 1994 May;(302):22-6.

5. Hudson D. The rotational profile: a study of lower limb axial torsion, hip rotation, and the foot progression angle in healthy adults. Gait Posture. 2016 Sep;49:426-30. Epub 2016 Aug 3.

6. Svenningsen S, Apalset K, Terjesen T, Anda S. Regression of femoral anteversion. A prospective study of intoeing children. Acta Orthop Scand. 1989 Apr;60(2):170-3.

7. Matovinović D, Nemec B, Gulan G, Sestan B, Ravlić-Gulan J. Comparison in regression of femoral neck anteversion in children with normal, intoeing and outtoeing gait—prospective study. Coll Antropol. 1998 Dec;22(2):525-32.

8. Dall'Oca C, Maluta T, Micheloni GM, Romeo T, Zambito A, Malagò R, Magnam B. Femoroacetabular impingement: biomechanical and dynamic considerations. Acta Biomed. 2014 Sep 24;85(Suppl 2):46-51.

9. Moussa M. Rotational malalignment and femoral torsion in osteoarthritic knees with patellofemoral joint involvement. A CT scan study. Clin Orthop Relat Res. 1994 Jul;(304):176-83.

10. Eckhoff DG. Effect of limb malrotation on malalignment and osteoarthritis. Orthop Clin North Am. 1994 Jul;25(3):405-14.

11. Eckhoff DG, Kramer RC, Alongi CA, VanGerven DP. Femoral anteversion and arthritis of the knee. J Pediatr Orthop. 1994 Sep-Oct;14(5):608-10.

12. Erkocak OF, Altan E, Altintas M, Turkmen F, Aydin BK, Bayar A. Lower extremity rotational deformities and patellofemoral alignment parameters in patients with anterior knee pain. Knee Surg Sports Traumatol Arthrosc. 2016 Sep;24(9):3011-20. Epub 2015 May 1.

13. Turner MS. The association between tibial torsion and knee joint pathology. Clin Orthop Relat Res. 1994 May;(302):47-51.

14. Turner MS, Smillie IS. The effect of tibial torsion of the pathology of the knee. J Bone Joint Surg Br. 1981;63-B(3):396-8.

15. Yagi T. Tibial torsion in patients with medial-type osteoarthrotic knees. Clin Orthop Relat Res. 1994 May;(302):52-6.

16. Audenaert EA, Peeters I, Vigneron L, Baelde N, Pattyn C. Hip morphological characteristics and range of internal rotation in femoroacetabular impingement. Am J Sports Med. 2012 Jun;40(6):1329-36. Epub 2012 Apr 2.

17. Staheli LT. Torsional deformity. Pediatr Clin North Am. 1977 Nov;24(4):799-811.

18. Kaiser P, Attal R, Kammerer M, Thauerer M, Hamberger L, Mayr R, Schmoelz W. Significant differences in femoral torsion values depending on the CT measurement technique. Arch Orthop Trauma Surg. 2016 Sep;136(9):1259-64. Epub 2016 Aug 8.

19. Yoshioka Y, Cooke TDV. Femoral anteversion: assessment based on function axes. J Orthop Res. 1987;5(1):86-91.

20. Katz K, Naor N, Merlob P, Wielunsky E. Rotational deformities of the tibia and foot in preterm infants. J Pediatr Orthop. 1990 Jul-Aug;10(4):483-5.

21. Fabry G, MacEwen GD, Shands AR Jr. Torsion of the femur. A follow-up study in normal and abnormal conditions. J Bone Joint Surg Am. 1973 Dec;55(8):1726-38.

22. Strecker W, Keppler P, Gebhard F, Kinzl L. Length and torsion of the lower limb. J Bone Joint Surg Br. 1997 Nov;79(6):1019-23.

23. Clementz BG, Magnusson A. Fluoroscopic measurement of tibial torsion in adults. A comparison of three methods. Arch Orthop Trauma Surg. 1989;108(3):150-3.

24. Lincoln TL, Suen PW. Common rotational variations in children. J Am Acad Orthop Surg. 2003 Sep-Oct;11(5):312-20.

25. Ruwe PA, Gage JR, Ozonoff MB, DeLuca PA. Clinical determination of femoral anteversion. A comparison with established techniques. J Bone Joint Surg Am. 1992 Jul;74(6):820-30.

26. Cibulka MT, Strube MJ, Meier D, Selsor M, Wheatley C, Wilson NG, Irrgang JJ. Symmetrical and asymmetrical hip rotation and its relationship to hip rotator muscle strength. Clin Biomech (Bristol, Avon). 2010 Jan;25(1):56-62.

27. Botser IB, Ozoude GC, Martin DE, Siddiqi AJ, Kuppuswami S, Domb BG. Femoral anteversion in the hip: comparison of measurement by computed tomography, magnetic resonance imaging, and physical examination. Arthroscopy. 2012 May;28(5):619-27. Epub 2012 Feb 1.

28. Souza RB, Powers CM. Concurrent criterion-related validity and reliability of a clinical test to measure femoral anteversion. J Orthop Sports Phys Ther. 2009 Aug;39(8):586-92.

29. Sangeux M, Mahy J, Graham HK. Do physical examination and CT-scan measures of femoral neck anteversion and tibial torsion relate to each other? Gait Posture. 2014 Jan;39(1):12-6. Epub 2013 Jun 18.

30. Kerr AM, Kirtley SJ, Hillman SJ, van der Linden ML, Hazlewood ME, Robb JE. The mid-point of passive hip rotation range is an indicator of hip rotation in gait in cerebral palsy. Gait Posture. 2003 Feb;17(1):88-91.

31. Mooney JF 3rd. Lower extremity rotational and angular issues in children. Pediatr Clin North Am. 2014 Dec;61(6):1175-83. Epub 2014 Sep 18.

32. Bleck EE. Metatarsus adductus: classification and relationship to outcomes of treatment. J Pediatr Orthop. 1983 Feb;3(1):2-9.

33. Scrutton DS, Robson P. The gait of 50 normal children. Physiotherapy. 1968 Oct; 54(10):363-8.

34. Schwartz RP, Heath AL, Morgan DW, Towns RC. A quantitative analysis of recorded variables in the walking pattern of "normal" adults. J Bone Joint Surg Am. 1964 Mar;46(2): 324-34.

35. Fabry G. Torsion of the femur. Acta Orthop Belg. 1977 Jul-Aug;43(4):454-9.

36. Rittmeister M, Hanusek S, Starker M. Does tibial rotation correlate with femoral anteversion? Implications for hip arthroplasty. J Arthroplasty. 2006 Jun;21(4):553-8.

37. Weinberg DS, Park PJ, Morris WZ, Liu RW. Femoral version and tibial torsion are not associated with hip or knee arthritis in a large osteological collection. J Pediatr Orthop. 2017 Mar;37(2):e120-8.

38. Stuberg W, Temme J, Kaplan P, Clarke A, Fuchs R. Measurement of tibial torsion and thigh-foot angle using goniometry and computed tomography. Clin Orthop Relat Res. 1991 Nov;(272):208-12.

39. Tamari K, Tinley P, Briffa K, Breidahl W. Validity and reliability of existing and modified clinical methods of measuring femoral and tibiofibular torsion in healthy subjects: use of different reference axes may improve reliability. Clin Anat. 2005 Jan;18(1):46-55.

40. Davids JR, Benfanti P, Blackhurst DW, Allen BL. Assessment of femoral anteversion in children with cerebral palsy: accuracy of the trochanteric prominence angle test. J Pediatr Orthop. 2002 Mar-Apr;22(2):173-8.

41. Shultz SJ, Nguyen AD, Windley TC, Kulas AS, Botic TL, Beynnon BD. Intratester and intertester reliability of clinical measures of lower extremity anatomic characteristics: implications for multicenter studies. Clin J Sport Med. 2006 Mar;16(2):155-61.

42. Kim HY, Lee SK, Lee NK, Choy WS. An anatomical measurement of medial femoral torsion. J Pediatr Orthop B. 2012 Nov;21(6): 552-7.

43. Chadayammuri V, Garabekyan T, Bedi A, Pascual-Garrido C, Rhodes J, O'Hara J, Mei-Dan O. Passive hip range of motion predicts femoral torsion and acetabular version. J Bone Joint Surg Am. 2016 Jan 20;98(2): 127-34.

44. Hunter DJ, Zhang Y, Niu J, Tu X, Amin S, Goggins J, Lavalley M, Guermazi A, Gale D, Felson DT. Structural factors associated with malalignment in knee osteoarthritis: the Boston Osteoarthritis Knee Study. J Rheumatol. 2005 Nov;32(11):2192-9.

45. Ramaswamy R, Kosashvili Y, Cameron HU, Cameron JC. Total knee replacement with rotational proximal tibial osteotomy for osteoarthritis with severe external tibial torsion and patellar instability. J Bone Joint Surg Br. 2009 Nov;91(11):1466-71.

46. Drexler M, Dwyer T, Marmor M, Reischl N, Attar F, Cameron J. Total knee arthroplasty in patients with excessive external tibial torsion >45° and patella instability—surgical technique and follow up. J Arthroplasty. 2013 Apr;28(4):614-9. Epub 2012 Nov 9.

47. Krackow KA. The technique of total knee arthroplasty. C.V. Mosby (St.Louis); 1990.

48. Dunn DM. Anteversion of the neck of the femur; a method of measurement. J Bone Joint Surg Br. 1952 May;34-B(2):181-6.

49. Dunlap K, Shands AR Jr, Hollister LC Jr, Gaul JS Jr, Streit HA. A new method for determination of torsion of the femur. J Bone Joint Surg Am. 1953 Apr;35(2):289-311.

50. Ryder CT, Crane L. Measuring femoral anteversion; the problem and a method. J Bone Joint Surg Am. 1953 Apr;35(2):321-8.

51. Magilligan DJ. Calculation of the angle of anteversion by means of horizontal lateral roentgenography. J Bone Joint Surg Am. 1956 Dec;38(6):1231-46.

52. Kuo TY, Skedros JG, Bloebaum RD. Measurement of femoral anteversion by biplane radiography and computed tomography imaging: comparison with an anatomic reference. Invest Radiol. 2003 Apr; 38(4):221-9.

53. Ruby L, Mital MA, O'Connor J, Patel U. Anteversion of the femoral neck. J Bone Joint Surg Am. 1979 Jan;61(1):46-51.

54. Güven M, Akman B, Unay K, Ozturan EK, Cakici H, Eren A. A new radiographic measurement method for evaluation of tibial torsion: a pilot study in adults. Clin Orthop Relat Res. 2009 Jul;467(7):1807-12. Epub 2008 Dec 4.

55. Hutter CG Jr, Scott W. Tibial torsion. J Bone Joint Surg Am. 1949 Jul;31(3):511-8.

56. Kulig K, Harper-Hanigan K, Souza RB, Powers CM. Measurement of femoral torsion by ultrasound and magnetic resonance imaging: concurrent validity. Phys Ther. 2010 Nov;90(11): 1641-8. Epub 2010 Aug 19.

57. Hudson D, Royer T, Richards J. Ultrasound measurements of torsions in the tibia and femur. J Bone Joint Surg Am. 2006 Jan;88(1): 138-43.

58. Moulton A, Upadhyay SS. A direct method of measuring femoral anteversion using ultrasound. J Bone Joint Surg Br. 1982;64(4):469-72.

59. Koenig JK, Pring ME, Dwek JR. MR evaluation of femoral neck version and tibial torsion. Pediatr Radiol. 2012 Jan;42(1):113-5. Epub 2011 Aug 13.

60. Beebe MJ, Wylie JD, Bodine BG, Kapron AL, Maak TG, Mei-Dan O, Aoki SK. Accuracy and reliability of computed tomography and magnetic resonance imaging compared with true anatomic femoral version. J Pediatr Orthop. 2017 Jun;37(4):e265-70.

61. Murphy SB, Simon SR, Kijewski PK, Wilkinson RH, Griscom NT. Femoral anteversion. J Bone Joint Surg Am. 1987 Oct; 69(8):1169-76.

62. Folinais D, Thelen P, Delin C, Radier C, Catonne Y, Lazennec JY. Measuring femoral and rotational alignment: EOS system versus computed tomography. Orthop Traumatol Surg Res. 2013 Sep;99(5):509-16. Epub 2013 Jul 19.

63. Waidelich HA, Strecker W, Schneider E. [Computed tomographic torsion-angle and length measurement of the lower extremity. The methods, normal values and radiation load]. [German.]. RoFo Fortschr Geb Rontgenstr Nuklearmed. 1992 Sep;157(3):245-51.

64. Hernandez RJ, Tachdjian MO, Poznanski AK, Dias LS. CT determination of femoral torsion. AJR Am J Roentgenol. 1981 Jul;137(1):97-101.

65. Jarrett DY, Oliveira AM, Zou KH, Snyder BD, Kleinman PK. Axial oblique CT to assess femoral anteversion. AJR Am J Roentgenol. 2010 May; 194(5):1230-3.

66. Byun HY, Shin H, Lee ES, Kong MS, Lee SH, Lee CH. The availability of radiological measurement of femoral anteversion angle: three-dimensional computed tomography reconstruction. Ann Rehabil Med. 2016 Apr; 40(2):237-43. Epub 2016 Apr 25.

67. Keppler P, Strecker W, Kinzl L. [CT determination of leg length and torsion in children and adolescents]. [German.]. Unfallchirurg. 1999 Dec;102(12):936-41.

68. Decker S, Suero EM, Hawi N, Müller CW, Krettek C, Citak M. The physiological range of femoral antetorsion. Skeletal Radiol. 2013 Nov; 42(11):1501-5. Epub 2013 Jul 16.

69. Seber S, Hazer B, Köse N, Göktürk E, Günal I, Turgut A. Rotational profile of the lower extremity and foot progression angle: computerized tomographic examination of 50 male adults. Arch Orthop Trauma Surg. 2000; 120(5-6):255-8.

70. Koerner JD, Patel NM, Yoon RS, Sirkin MS, Reilly MC, Liporace FA. Femoral version of the general population: does "normal" vary by gender or ethnicity? J Orthop Trauma. 2013 Jun; 27(6):308-11.

71. Duparc F, Thomine JM, Simonet J, Biga N. Femoral and tibial bone torsions associated with medial femoro-tibial osteoarthritis. Index of cumulative torsions. Orthop Traumatol Surg Res. 2014 Feb;100(1):69-74. Epub 2014 Jan 20.

72. Jaarsma RL, Bruggeman AWA, Pakvis DFM, Verdonschot N, Lemmens JAM, van Kampen A. Computed tomography determined femoral torsion is not accurate. Arch Orthop Trauma Surg. 2004 Oct;124(8):552-4. Epub 2004 Aug 7.

73. Reikerås O, Høiseth A. Torsion of the leg determined by computed tomography. Acta Orthop Scand. 1989 Jun;60(3):330-3.

74. Liodakis E, Doxastaki I, Chu K, Krettek C, Gaulke R, Citak M, Kenawey M. Reliability of the assessment of lower limb torsion using computed tomography: analysis of five different techniques. Skeletal Radiol. 2012 Mar;41(3):305-11. Epub 2011 May 11.

75. Tomczak RJ, Guenther KP, Rieber A, Mergo P, Ros PR, Brambs HJ. MR imaging measurement of the femoral antetorsional angle as a new technique: comparison with CT in children and adults. AJR Am J Roentgenol. 1997 Mar;168(3):791-4.

76. Jakob RP, Haertel M, Stüssi E. Tibial torsion calculated by computerised tomography and compared to other methods of measurement. J Bone Joint Surg Br. 1980 May;62-B(2):238-42.

77. Widjaja PM, Ermers JW, Sijbrandij S, Damsma H, Klinkhamer AC. Technique of torsion measurement of the lower extremity using computed tomography. J Comput Assist Tomogr. 1985 May-Jun;9(3):466-70.

78. Brenner D, Elliston C, Hall E, Berdon W. Estimated risks of radiation-induced fatal cancer from pediatric CT. AJR Am J Roentgenol. 2001 Feb;176(2):289-96.

79. Smith-Bindman R, Lipson J, Marcus R, Kim KP, Mahesh M, Gould R, Berrington de González A, Miglioretti DL. Radiation dose associated with common computed tomography examinations and the associated lifetime attributable risk of cancer. Arch Intern Med. 2009 Dec 14;169(22):2078-86.

80. Arai N, Nakamura S, Matsushita T, Suzuki S. Minimal radiation dose computed tomography for measurement of cup orientation in total hip arthroplasty. J Arthroplasty. 2010 Feb;25(2):263-7. Epub 2009 May 12.

81. Chaibi Y, Cresson T, Aubert B, Hausselle J, Neyret P, Hauger O, de Guise JA, Skalli W. Fast 3D reconstruction of the lower limb using a parametric model and statistical inferences and clinical measurements calculation from biplanar X-rays. Comput Methods Biomech Biomed Engin. 2012;15(5):457-66. Epub 2011 May 24.

82. Than P, Szuper K, Somoskeöy S, Warta V, Illés T. Geometrical values of the normal and arthritic hip and knee detected with the EOS imaging system. Int Orthop. 2012 Jun;36(6):1291-7. Epub 2011 Nov 18.

83. Deschênes S, Charron G, Beaudoin G, Labelle H, Dubois J, Miron MC, Parent S. Diagnostic imaging of spinal deformities: reducing patients radiation dose with a new slot-scanning X-ray imager. Spine. 2010 Apr 20;35(9):989-94.

84. Guenther KP, Tomczak R, Kessler S, Pfeiffer T, Puhl W. Measurement of femoral anteversion by magnetic resonance imaging—evaluation of a new technique in children and adolescents. Eur J Radiol. 1995 Nov;21(1):47-52.

85. Schneider B, Laubenberger J, Jemlich S, Groene K, Weber HM, Langer M. Measurement of femoral antetorsion and tibial torsion by magnetic resonance imaging. Br J Radiol. 1997 Jun;70(834):575-9.

86. Georgiadis AG, Siegal DS, Scher CE, Zaltz I. Can femoral rotation be localized and quantified using standard CT measures? Clin Orthop Relat Res. 2015 Apr;473(4):1309-14.

87. Dejour H, Walch G, Nove-Josserand L, Guier C. Factors of patellar instability: an anatomic radiographic study. Knee Surg Sports Traumatol Arthrosc. 1994;2(1):19-26.

88. Caylor D, Fites R, Worrell TW. The relationship between quadriceps angle and anterior knee pain syndrome. J Orthop Sports Phys Ther. 1993 Jan;17(1):11-6.

89. Parikh S, Noyes FR. Patellofemoral disorders: role of computed tomography and magnetic resonance imaging in defining abnormal rotational lower limb alignment. Sports Health. 2011 Mar;3(2):158-69.

90. Bruce WD, Stevens PM. Surgical correction of miserable malalignment syndrome. J Pediatr Orthop. 2004 Jul-Aug;24(4):392-6.

91. Takai S, Sakakida K, Yamashita F, Suzu F, Izuta F. Rotational alignment of the lower limb in osteoarthritis of the knee. Int Orthop. 1985;9(3):209-15.

92. Lee TQ, Anzel SH, Bennett KA, Pang D, Kim WC. The influence of fixed rotational deformities of the femur on the patellofemoral contact pressures in human cadaver knees. Clin Orthop Relat Res. 1994 May;(302):69-74.

93. Gelberman RH, Cohen MS, Shaw BA, Kasser JR, Griffin PP, Wilkinson RH. The association of femoral retroversion with slipped capital femoral epiphysis. J Bone Joint Surg Am. 1986 Sep;68(7):1000-7.

94. Ito K, Minka MA 2nd, Leunig M, Werlen S, Ganz R. Femoroacetabular impingement and the cam-effect. A MRI-based quantitative anatomical study of the femoral head-neck offset. J Bone Joint Surg Br. 2001 Mar;83(2):171-6.

95. Ganz R, Parvizi J, Beck M, Leunig M, Nötzli H, Siebenrock KA. Femoroacetabular impingement: a cause for osteoarthritis of the hip. Clin Orthop Relat Res. 2003 Dec;(417):112-20.

96. Terjesen T, Benum P, Anda S, Svenningsen S. Increased femoral anteversion and osteoarthritis of the hip joint. Acta Orthop Scand. 1982 Aug;53(4):571-5.

97. Halpern AA, Tanner J, Rinsky L. Does persistent fetal femoral anteversion contribute to osteoarthritis?: a preliminary report. Clin Orthop Relat Res. 1979 Nov-Dec;(145):213-6.

98. Tönnis D, Heinecke A. Acetabular and femoral anteversion: relationship with osteoarthritis of the hip. J Bone Joint Surg Am. 1999 Dec;81(12):1747-70.

99. Hubbard DD, Staheli LT, Chew DE, Mosca VS. Medial femoral torsion and osteoarthritis. J Pediatr Orthop. 1988 Sep-Oct;8(5):540-2.

100. Kitaoka HB, Weiner DS, Cook AJ, Hoyt WA Jr, Askew MJ. Relationship between femoral anteversion and osteoarthritis of the hip. J Pediatr Orthop. 1989 Jul-Aug;9(4):396-404.

101. Krackow KA, Mandeville DS, Rachala SR, Bayers-Thering M, Osternig LR. Torsion deformity and joint loading for medial knee osteoarthritis. Gait Posture. 2011 Apr;33(4):625-9. Epub 2011 Mar 24.

102. Eckhoff DG, Johnston RJ, Stamm ER, Kilcoyne RF, Wiedel JD. Version of the osteoarthritic knee. J Arthroplasty. 1994 Feb;9(1):73-9.

103. Hollister AM, Jatana S, Singh AK, Sullivan WW, Lupichuk AG. The axes of rotation of the knee. Clin Orthop Relat Res. 1993 May;(290):259-68.

104. Hicks J, Arnold A, Anderson F, Schwartz M, Delp S. The effect of excessive tibial torsion on the capacity of muscles to extend the hip and knee during single-limb stance. Gait Posture. 2007 Oct;26(4):546-52. Epub 2007 Jan 16.

105. Staheli LT. Torsion—treatment indications. Clin Orthop Relat Res. 1989 Oct;(247):61-6.

106. Gordon JE, Pappademos PC, Schoenecker PL, Dobbs MB, Luhmann SJ. Diaphyseal derotational osteotomy with intramedullary fixation for correction of excessive femoral anteversion in children. J Pediatr Orthop. 2005 Jul-Aug;25(4):548-53.

107. Svenningsen S, Terjesen T, Apalset K, Anda S. Osteotomy for femoral anteversion. A prospective 9-year study of 52 children. Acta Orthop Scand. 1990 Aug;61(4):360-3.

108. MacEwen GD. Anteversion of the femur. Postgrad Med. 1976 Oct;60(4):154-6.

109. Moens P, Lammens J, Molenaers G, Fabry G. Femoral derotation for increased hip anteversion. A new surgical technique with a modified Ilizarov frame. J Bone Joint Surg Br. 1995 Jan;77(1):107-9.

110. Chapman ME, Duwelius PJ, Bray TJ, Gordon JE. Closed intramedullary femoral osteotomy. Shortening and derotation procedures. Clin Orthop Relat Res. 1993 Feb;(287):245-51.

111. Winquist RA. Closed intramedullary osteotomies of the femur. Clin Orthop Relat Res. 1986 Nov(212:155-64.

112. Gérard R, Stindel E, Moineau G, Le Nen D, Lefèvre C. Rotational femoral osteotomies using an endomedullary saw. Orthop Traumatol Surg Res. 2009 Oct;95(6):414-9. Epub 2009 Aug 14.

113. Svenningsen S, Apalset K, Terjesen T, Anda S. Osteotomy for femoral anteversion. Complications in 95 children. Acta Orthop Scand. 1989 Aug;60(4):401-5.

114. Hammouda AI, Jauregui JJ, Gesheff MG, Standard SC, Herzenberg JE. Trochanteric entry for femoral lengthening nails in children: is it safe? J Pediatr Orthop. 2017 Jun;37(4):258-64.

115. Keeler KA, Dart B, Luhmann SJ, Schoenecker PL, Ortman MR, Dobbs MB, Gordon JE. Antegrade intramedullary nailing of pediatric femoral fractures using an interlocking pediatric femoral nail and a lateral trochanteric entry point. J Pediatr Orthop. 2009 Jun;29(4):345-51.

116. Schottel PC, Hinds RM, Lazaro LE, Klinger C, Ni A, Dyke JP, Helfet DL, Lorich DG. The effect of antegrade femoral nailing on femoral head perfusion: a comparison of piriformis fossa and trochanteric entry points. Arch Orthop Trauma Surg. 2015 Apr;135(4):473-80. Epub 2015 Feb 24.

117. Lowe JA, Min W, Lee MA, Wolinsky PR. Risk of injury to the superior gluteal nerve when using a proximal incision for insertion of a piriformis-entry reamed femoral intramedullary nail: a cadaveric study. J Bone Joint Surg Am. 2012 Aug 1;94(15):1416-9.

118. Ricci WM, Schwappach J, Tucker M, Coupe K, Brandt A, Sanders R, Leighton R. Trochanteric versus piriformis entry portal for the treatment of femoral shaft fractures. J Orthop Trauma. 2006 Nov-Dec;20(10):663-7.

119. Mylle J, Lammens J, Fabry G. Derotation osteotomy to correct rotational deformities of the lower extremities in children. A comparison of three methods. Acta Orthop Belg. 1993;59(3):287-92.

120. Dodgin DA, De Swart RJ, Stefko RM, Wenger DR, Ko JY. Distal tibial/fibular derotation osteotomy for correction of tibial torsion: review of technique and results in 63 cases. J Pediatr Orthop. 1998 Jan-Feb;18(1):95-101.

121. Savva N, Ramesh R, Richards RH. Supramalleolar osteotomy for unilateral tibial torsion. J Pediatr Orthop B. 2006 May;15(3):190-3.

122. Erschbamer M, Gerhard P, Klima H, Ellenrieder B, Zdenek-Lehnen K, Giesinger K. Distal tibial derotational osteotomy with external fixation to treat torsional deformities: a review of 71 cases. J Pediatr Orthop B. 2017 Mar;26(2):179-83.

123. MacWilliams BA, McMulkin ML, Baird GO, Stevens PM. Distal tibial rotation osteotomies normalize frontal plane knee moments. J Bone Joint Surg Am. 2010 Dec 1;92(17):2835-42.

124. Inan M, Ferri-de Baros F, Chan G, Dabney K, Miller F. Correction of rotational deformity of the tibia in cerebral palsy by percutaneous supramalleolar osteotomy. J Bone Joint Surg Br. 2005 Oct;87(10):1411-5.

125. Krengel WF 3rd, Staheli LT. Tibial rotational osteotomy for idiopathic torsion. A comparison of the proximal and distal osteotomy levels. Clin Orthop Relat Res. 1992 Oct;(283):285-9.

126. Rattey T, Hyndman J. Rotational osteotomies of the leg: tibia alone versus both tibia and fibula. J Pediatr Orthop. 1994 Sep-Oct;14(5):615-8.

127. Bennett JT, Bunnell WP, MacEwen GD. Rotational osteotomy of the distal tibia and fibula. J Pediatr Orthop. 1985 May-Jun;5(3):294-8.

128. de Roode CP, Hung M, Stevens PM. Supramalleolar osteotomy: a comparison of fixation methods. J Pediatr Orthop. 2013 Sep;33(6):672-7.

129. Stotts AK, Stevens PM. Tibial rotational osteotomy with intramedullary nail fixation. Strateg Trauma Limb Reconstr. 2009 Dec;4(3):129-33. Epub 2009 Nov 26.

130. Horn DM, Fragomen AT, Rozbruch SR. Supramalleolar osteotomy using circular external fixation with six-axis deformity correction of the distal tibia. Foot Ankle Int. 2011 Oct;32(10):986-93.

131. Mayer SW, Hubbard EW, Sun D, Lark RK, Fitch RD. Gradual deformity correction in Blount disease [Epub ahead ofprint]. J Pediatr Orthop. 2016 Dec 23.

132. Fragomen AT, Meade M, Borst E, Nguyen J, Rozbruch SR. Does the surgical correction of tibial torsion with genu varum produce outcomes similar to those in varus correction alone? J Knee Surg. 2018 Apr;31(4):359-69. Epub 2017 Jun 24.

133. Clarke SE, McCarthy JJ, Davidson RS. Treatment of Blount disease a comparison between the multiaxial correction system and other external fixators. J Ped Orthop.

134. Rozbruch SR, Segal K, Ilizarov S, Fragomen AT, Ilizarov G. Does the Taylor Spatial Frame accurately correct tibial deformities? Clin Orthop Relat Res. 2010 May;468(5):1352-61. Epub 2009 Nov 13.

135. Flandry F, Hughston JC. Complications of extensor mechanism surgery for patellar malalignment. Am J Orthop. 1995 Jul;24(7):534-43.

136. Fragomen AT, Rozbruch SR. Retrograde magnetic internal lengthening nail for acute femoral deformity correction and limb lengthening. Expert Rev Med Devices. 2017 Oct;14(10):811-20. Epub 2017 Sep 17.

137. Meister K, James SL. Proximal tibial derotation osteotomy for anterior knee pain in the miserably malaligned extremity. Am J Orthop. 1995 Feb;24(2):149-55.

138. Stevens PM, Gililland JM, Anderson LA, Mickelson JB, Nielson J, Klatt JW. Success of torsional correction surgery after failed surgeries for patellofemoral pain and instability. Strateg Trauma Limb Reconstr. 2014 Apr;9(1):5-12. Epub 2013 Dec 15.