JB&JS
OPEN ACCESS

Mechanical Axis Deviation Shift in Limb Lengthening Over the Anatomical Axis, a Retrospective Analysis

Akram Al Ramlawi, MD, Philip K. McClure, MD, John E. Herzenberg, MD, and Michael Assayag, MD

Investigation performed at the International Center for Limb Lengthening, Baltimore, MD

Background: Recently, limb lengthening devices have shifted from external fixators to telescoping magnetic intramedullary lengthening nails (MILNs), which lengthen strictly along the bone's anatomic axis. Baumgart proposed the reverse planning method, overcorrecting lateral shift with a distal osteotomy and slight varus angulation. The untested assumption that antegrade lengthening along the anatomic axis causes lateral mechanical axis deviation (MAD) prompted our study, which examines MILNs' effect on lower limb alignment.

Methods: We retrospectively evaluated records for 154 femoral antegrade MILNs inserted in 122 adult patients for limb lengthening. We excluded patients who underwent concomitant corrective osteotomies or tibial lengthening, or who had malunion, nonunion, mechanical failure, or revision surgery for any reason. Long-leg standing radiographs were taken preoperatively, at the end of lengthening, around 3 months postoperatively, and at the culmination of consolidation (approximately 6 months postoperatively). MAD and anatomic mechanical angle (AMA) were assessed as primary outcomes at each radiographic time point for sequential comparison. The predicted MAD was derived from the trigonometric formula (Predicted MAD = lengthening × sin [AMA]).

Results: Average preoperative MAD was 2.4 mm medial (SD = 10.6), diminishing to 1.9 mm medial (SD = 13.2) by the end of lengthening. On assessment at consolidation, average MAD had equilibrated back to 2.6 mm medial. Our results showed a net shift of 0.18 mm, whereas the predicted shift was 5.4 mm. The mean preoperative AMA was 5.9 mm (SD = 1.49). At the end of lengthening, the average AMA had decreased to 4.8 mm (SD = 1.4).

Conclusion: Our data indicated minimal to no impact on the mechanical axis or joint alignment of the lower limb after antegrade lengthening using a telescoping femoral MILN in a deformity-free femur. Study results suggested that the femur typically realigned in a way that minimized mechanical deviation while preserving joint alignment.

Level of Evidence: Level III. See Instructions for Authors for a complete description of levels of evidence.

Introduction

Recently, magnetic internal lengthening nails (MILNs) have become the preferred implant for distraction osteogenesis of lower extremity long bones in adults[1]. Improvements in patient experience and ease of physical therapy, relative to classical external fixation lengthening, have led to the use of the internal devices whenever possible for limb lengthening[1-3]. The Fitbone internal lengthening nails were first introduced in 1997[4,5]; subsequently, the Precice magnetic internal lengthening nails were first widely introduced in 2012[6]. Both have become a staple of the modern limb lengthening approach.

Intramedullary (IM) nails offer advantages such as reducing the risk of pin site infections and improving patient comfort. All IM nails are constrained to lengthen only along the anatomic axis of the bone, unlike external fixators, which can be adjusted to lengthen along both the mechanical and anatomic axes. In addition, certain external fixator devices offer up to 6° of freedom in manipulating bone fragments[7]. A concept of acute deformity correction followed by distraction along the anatomic axis was first put forward by Baumgart et al.[8] and has since been modified and adapted by other authors, such as the Bone Ninja Reverse Planning Method (RPM)[9] and the Resolution Axis Method[10]. The restriction

Potential Conflicts of Interest and Funding Sources: None are declared.

Disclosure: The **Disclosure of Potential Conflicts of Interest** forms are provided with the online version of the article (http://links.lww.com/JBJSOA/A765).

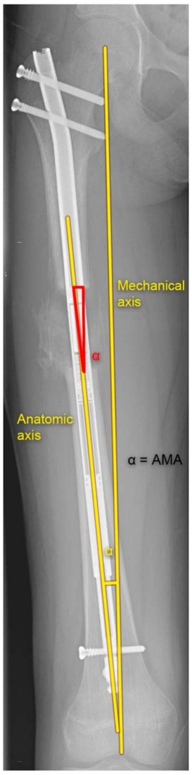


Fig. 1
MAD shift derivation: The figure shows how calculated MAD shift is derived, with Alpha equal to AMA. The yellow lines correspond to the mechanical and anatomical axis of the femur, and the red lines correspond to the projected mechanical segment of the lengthened part and its anatomical segments, which is parallel and equal to the distance of lengthening. AMA = anatomic mechanical angle, and MAD = mechanical axis deviation.

to anatomic lengthening has been a theoretical drawback for using antegrade MILN due to fear of deviating the mechanical axis and subsequently affecting neighboring joints' function and alignment[8,11]. Nevertheless, 2 studies have been published on lower limb alignment anatomic antegrade lengthening, and these case series found that the bending of the femur into slight varus counterbalanced the valgus from lengthening along the anatomic axis, and from clinically affecting the MAD[12]. Furthermore, another study on using the IM skeletal kinetic distractor (ISKD) nail on 26 limbs showed that 15 limbs had an insignificant total lateral change in MAD of ≤2 mm. The remaining 11 limbs underwent a mean lateral shift in MAD of 2.0 mm/cm of lengthening (1.0-3.5 mm/cm)[13].

Currently, there is a lack of consensus in the literature on whether a clinically significant MAD shift takes place after modern MILN lengthening, and, subsequently, whether preoperative pre-emptive planning is necessary to counteract this shift. Furthermore, the effect of anatomic lengthening along the anatomic axis with antegrade MILN has not been reviewed in a large patient cohort. The aim of our study was to explore the effect of the MILN on the alignment and the mechanical axis of the lower limb.

Methods

Our data set includes 537 limb lengthening cases using IM nails from a single center. All patients' medical data were retrospectively reviewed. After excluding pediatric patients and patients with less than 12 months of follow-up, we excluded patients who underwent concomitant secondary realignment osteotomies (86), tibial lengthening (46), had preoperative malunion (23), severe preoperative deformity of the lower limb, including rotational, (82), nonunion (32), mechanical failure (28), or revision surgery for any reason (52). Lack of optimal radiographic technique at any of the 3 stages of examination was also considered as an exclusion criterion (34). Erect leg film with appropriate lifting under the short leg as needed, and patella forward position was reviewed on the final radiographic view by both a radiology technician at the time of obtaining the film and the attending surgeon at the time of review. Average age at time of surgery was 20.5 years (minimum age 16 years and maximum age 59 years). All MILNs were inserted through the greater trochanter (79) or piriformis (75). Our final cohort, after reviewing the inclusion and exclusion criteria, includes 154 Precice nails inserted in 122 adult patients who underwent IM nail limb lengthening.

Long standing radiographs were taken preoperatively, at the end of lengthening (EOL: around 3 months postoperatively) and at the end of consolidation (around 6 months postoperatively). Consolidation was defined as full healing and bone formation at the osteotomy site as evidenced by a lower limb radiograph. Full healing was defined by the radiographic confirmation of bone bridging at the osteotomy site covering all 4 (anterior, posterior, medial, and lateral) cortical surfaces as seen on anteroposterior and lateral imaging. All radiographs were assessed by trained personnel, and radiographic images were taken by a trained certified technician and calibrated with a 1-inch external magnification ball. Preoperative and postoperative radiographs were compared. Measurements were taken using Picture Archiving Communication System Intelerad, by 2 authors, A.A.R. and M.A. To assess intraobserver and interobserver reliability, a second round of all radiologic assessments was conducted 1 week later. The intraclass correlation coefficient (ICC) for intraobserver reliability yielded a value of 0.973, while the ICC for interobserver reliability was 0.913. A p value below 0.05 was considered statistically significant.

Operative Technique

The tip of either the greater trochanter or the piriformis fossa, based on the chosen insertion site, was identified, along with the proposed nail length. Osteotomy level was determined by the apex

TABLE I Demographic Distribution of Patients

Demographics	Mean	Standard Deviation
Age (yrs)	20.4	14
Weight (kg)	61.7	16
Body mass index	22.9	4

TABLE II MAD Shift at Consolidation Compared with Predicted MAD Shift

MAD Shift	Mean	St. Dev
Predicted MAD shift (mm)	5.4	2.78
MAD shift (mm)	0.187*	7.08

*p < 0.05 compared with predicted MAD shift. MAD = mechanical axis deviation.

of the sagittal bow seen on preoperative radiographs because all MILNs have a completely straight profile in the sagittal plane. Under tourniquet control, through a 2- to 3-cm lateral incision at the superior pole of the patella, the iliotibial band was incised anteriorly to the extensor mechanism and posteriorly to the intermuscular septum. The leg was then adducted, and the entry point was identified percutaneously under fluoroscopic control, using a 1.8-mm wire. This determined the entry point in the skin, and a 2-cm incision was made. Subsequently, a 3.2-mm Steinmann pin was inserted at the entry point, and its positioning was verified under fluoroscopy. Multiple drill holes were created at the planned osteotomy level through a small lateral thigh incision, using a 4.8-mm solid drill bit. This predrilling of the osteotomy site served to vent the canal to help prevent fat embolism during reaming and to accelerate the healing of the osteotomy (the reaming exit the vent holes and act as prepositioned bone graft). An anterior cruciate ligament reamer was used to broach the proximal femur, and a long beaded guide rod was inserted, followed by flexible reamers sequentially in 0.5- to 1-mm increments until ~2.0 mm over the nail diameter. Rotational markers were inserted using a 3.2-mm Steinmann pin or 5- to 6-mm half pin, placed collinearly—one in the lesser trochanter and the second at the distal metaphysis. The purpose of the rotational markers was to prevent inadvertent malrotation. The beaded guide wire was then removed, and the MILN was inserted up to the osteotomy site. The osteotomy was completed with an osteotome, confirmed by fragment translation under fluoroscopy. The nail was then advanced in the canal, and its position was verified under fluoroscopy before being locked proximally and distally in a standard manner. The magnet was marked on the skin for reference, and 1 mm of distraction was completed to demonstrate nail function. A latency period of 5 to 7 days was observed, with distraction rates between 0.5 and 1 mm per day, depending on regenerate formation and response to physical therapy. Radiographic follow-ups took place every 2 weeks to make necessary adjustments, and weight-bearing recommendations adhered to implant limitations and guidelines.

Extracted Data

Type of nail (Trochanteric vs Piriformis) and diameter of nail were reported. Furthermore, lengthening latency period, initial and final rates, and rhythms of lengthening, along with the target of lengthening at the end of the procedure, were all extracted from the patients' charts.

Primary Outcomes

MAD and anatomic mechanical angle (AMA) were primary outcomes. The mechanical axis of the lower limb is the line passing through the center of the hip joint and the center of the ankle joint, and the MAD was measured as the perpendicular distance from that line to the center of the knee joint. The AMA

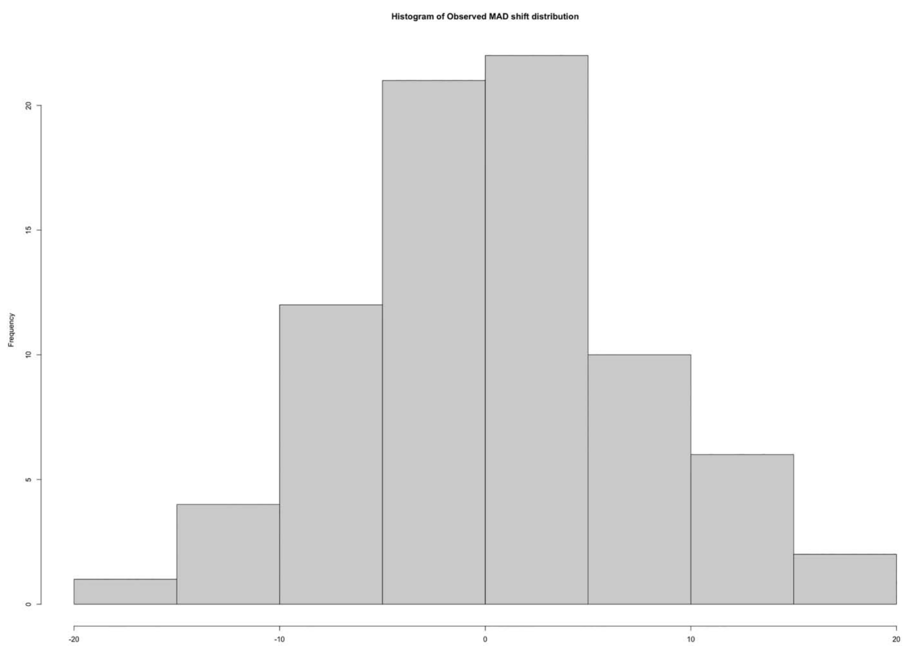


Fig. 2

Histogram showing individual perceived distribution of MAD shift. MAD = mechanical axis deviation.

was measured as the angle between the mechanical axis of the femur and the anatomic axis of the femur, defined as the equidistant line from the medial and lateral cortices. These angles were compared preoperatively and postoperatively.

- Net MAD is the sum of the overall MAD, with lateral shift having a (+) sign and medial shift having a (−) sign,
- The predicted MAD is derived from the trigonometric formula: Predicted MAD shift = lengthening × sin (AMA) (Fig. 1).

Secondary Outcomes

Anatomic medial proximal femoral angle, mechanical lateral distal femoral angle (mLDFA), medial proximal tibial angle (MPTA), lateral distal tibial angle (LDTA), and femur height (distance from tip of femoral head to medial femoral epicondyle) were measured preoperatively, postoperatively, or both, and nail bend was also assessed at consolidation. Preoperative radiographic outcomes were then used to build a predictive model for MAD shift. Nail bend was assessed radiographically by measuring the angle between the distal and proximal axes of the nail.

Statistical Analysis

The statistical software, R version 4.3.1 (Comprehensive R Archive Network, GNU General Public License), was used for all statistical analyses. All continuous variables were tested for normality using the Shapiro-Wilk test followed normal distribution. The Student T test and linear regression were used for hypothesis testing. Each continuous measurement is expressed as mean ± SD with range.

Results

We retrospectively inspected 154 femurs in 122 patients. The study group was composed of 83 male patients and 71 female patients, with a mean age of 20.45 years. Average weight was 61.7 kg, and average follow-up time was 16 months after surgery ranging from 12 to 22 months. (Table I)

Primary Outcomes

The average preoperative MAD of the study cohort was as follows: 12 femurs had a MAD of 0 mm, 50 had a lateral MAD with an average of 7.4 mm, and 92 had a medial MAD with an average of 7.4 mm and a net deviation of 2.4 mm medially. At EOL, average MAD changed to 1.9 mm medial. At consolidation, average MAD changed to 2.6 mm medial. In terms of MAD shift, our results showed a net shift of 0.18 mm, whereas the predicted MAD shift was 5.4 mm lateral, the predicted and observed net MAD shift difference was statistically significantt ($p < 0.05$) (Table II). Figures 2 and 3 shows the frequency and distribution of the observed and theoretical MAD shifts.

For femurs undergoing net lateral shift in MAD at consolidation (Table III), MAD was −3.38 mm medial preoperatively, and at EOL, it was 1.6 mm lateral, and at consolidation, MAD was 2.2 mm lateral. The average difference between preoperative and consolidation value was 5.61 mm lateral, whereas the predicted was 0.27 mm lateral, $p < 0.05$.

For femurs undergoing medial shift in MAD at consolidation compared with preoperatively (Table III), MAD was 1.4 mm medial preoperatively, and at EOL, it was 5.76 mm medial, and at consolidation, MAD was 7.15 mm

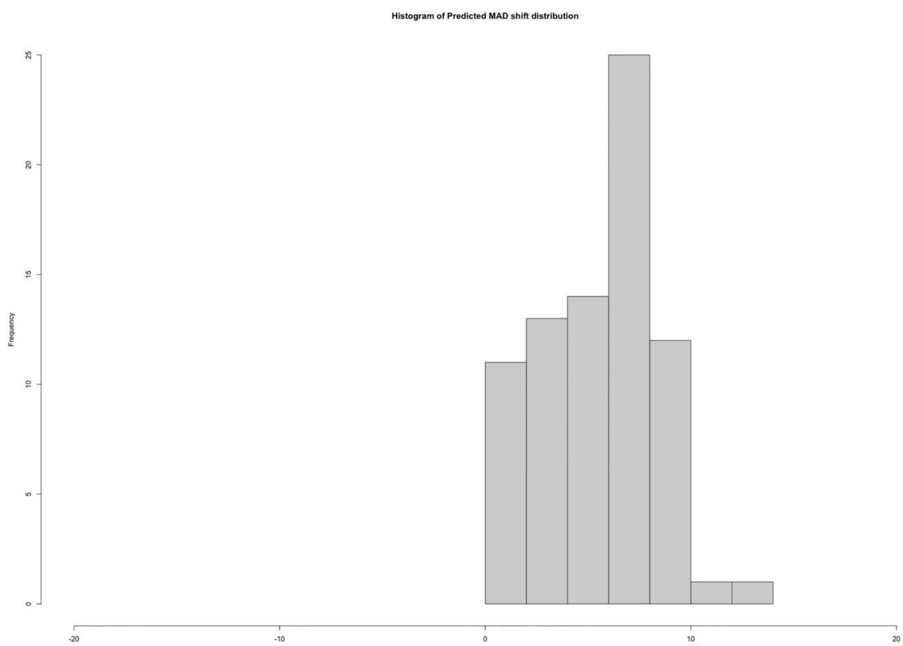


Fig. 3
Histogram showing individual theoretical distribution of MAD shift. MAD = mechanical axis deviation.

TABLE III Average MAD and MAD Shifts Subcategorized in Terms of Lateral and Medial MAD Shift at the End of Lengthening

	Lateral Shift		Medial Shift	
Radiographic Outcomes	Mean	SD	Mean	SD
Preoperative MAD (mm)	3.4	10.1	−1.4	11.1
End of lengthening MAD (mm)	1.6*	10.6	5.7*	14.9
Consolidation MAD (mm)	2.2*	4.1	7.15*	11.5
MAD shift at consolidation	5.6	10.4	−5.7	11.6
Predicted MAD shift (mm)	4.8**	2.7	6**	2.8
Total Lengthening (cm)	5.1	2.7	6.6	2.34
Avg observed MAD shift/1 cm of lengthening	1.1		−0.9	

*p < 0.05 compared with preoperative MAD. **p < 0.05 compared with consolidation MAD shift. MAD = mechanical axis deviation, and SD = standard deviation.

medial. The average difference between preoperative and consolidation value was 5.7 mm medial, whereas the predicted was 1.2 mm lateral, $p < 0.05$.

Furthermore, predicted MAD shift was found to be 5.4 mm lateral whereas our observed MAD was 0.18 mm lateral (Table III). In terms of femoral AMA, the average preoperative femoral AMA was 5.9°. At EOL, the average femoral AMA was decreased to 4.8°, and at the end of healing, the average femoral AMA was decreased to 4.7°. The difference between femoral AMA preoperatively and at consolidation was statistically significant ($p < 0.05$) (Table IV).

Table V presents the results of multiple linear regression analyses assessing potential demographic and radiographic factors associated with MAD lateral shift. No factors were found to be statistically significant. Further analysis, focusing on patients with a lateral MAD shift greater than 5°, identified a subset of 8 individuals. Table VI details the demographic and radiographic characteristics of these patients, though no significant patterns emerged from this subgroup.

Secondary Outcomes

In terms of preoperative, EOL and consolidation radiographic measurements were all within reference range (Table IV).

In terms of nail characteristics, the average nail diameter was 10.9 ± 1.2 mm, with average nail bend, and at consolidation of 2.4 ± 2.4°, the ratio of weight to nail diameter was 5.9 ± 1.3 kg/mm (Tables VII and VIII).

Discussion

Our study showed minimal change in mechanical axis from baseline despite antegrade lengthening along the mechanical axis. There was a trend toward more varus alignment at

TABLE IV Preoperative, End of Lengthening, and Consolidation Radiographic Measurements

	Preoperative		End of Lengthening		Consolidation	
Radiographic Outcomes	Mean	SD	Mean	SD	Mean	SD
Femoral length (cm)	42.1	5.6			47.1	7.3
mLDFA (°)	88.7	4.9	88.1	4.6	88.0	5.6
mMPTA (°)	88.0	3.2	87.6	2.9	87.2	3.0
mLDTA (°)	87.5	5.4				
NSA (°)	129.0	7.5				
AMA (°)	6.1	1.4	4.8*	1.4	4.7*	1.7
JLCA (°)	1.3	1.3	1.2	1.5		
Nail bend (°)			2.4	2.4		
Lengthening (cm)					5.8	2.9

*p value < 0.05 compared with preoperative MAD. AMA = anatomic mechanical angle, JLCA = joint line convergence angle, mLDFA = mechanical lateral distal femoral angle, mLDTA = mechanical lateral distal tibial angle, mMPTA = mechanical medial proximal tibial angle, NSA = neck shaft angle, and SD = standard deviation.

JBJS Open Access • 2025:e24.00168. **openaccess.jbjs.org**

TABLE V Linear Regression of Different Preoperative Radiographic and Demographic Characteristics on MAD Shift

	Dependent Variable: MAD Shift
AMA preoperative	0.539 (0.458)
mLDFA preoperative	0.116 (0.114)
mLDTA preoperative	−0.045 (0.105)
Weight (kg)	−0.105 (0.056)
Body mass index	0.063 (0.182)
Constant	−2.724 (15.488)
Observations	73
R2	0.084
Adjusted R2	0.016
Residual Std. Error	5.348 (df = 67)
F Statistic	1.228 (df = 5; 67)

None were statistically significant. AMA = anatomic mechanical angle, MAD = mechanical axis deviation, mLDFA = mechanical lateral distal femoral angle, mLDTA = mechanical lateral distal tibial angle, and SD = standard deviation.

completion of lengthening in patients with preoperative varus MAD. Furthermore, AMA decreased significantly after lengthening. We also noticed a statistically significant relationship between nail bending and the nail diameter over patient weight ratio, and the effect of nail bending on lower limb alignment is depicted in Figure 4.

A previous study by Burghradt et al.[13] found that the average lateral MAD shift between preoperative and postconsolidation after IM limb lengthening of 27 patients using an ISKD nail was estimated to be 1 mm of lateral shift for every 1 cm of lengthening. Our study showed that 49% of the cohort had a lateral shift, and 51% had a medial shift. Furthermore, similar to the study by Burghradt et al.[13], our MAD range was too wide and suggested that a simple predictive model will not be effective in predicting the MAD shift despite a much larger series. The difference between our results and the literature could be due to the limited number of patients analyzed in the ISKD article. On the other hand, other studies reported no difference in MAD in prelengthening and postlengthening; however, these studies had patients who did concomitant tibial lengthening, had a concomitant deformity correction, or had an external fixator applied during the lengthening phase[2,12].

TABLE VII Average Nail Diameter Along with the Ratio of Patient Weight Over Nail Diameter and Average Nail Bend

Nail	Mean	Standard Deviation
Diameter	10.9	1.2
Weight (kg)/diameter (mm)	5.9	1.3
Nail bend (°)	2.4	2.4

Our study demonstrates no predictable change in direction of the lower limb's MAD after MILN, and when actual MAD change was compared with theoretical MAD change, a significant difference between both measurements was appreciated, strengthening our hypothesis that MAD change does not follow a simple linear trigonometric relationship with lengthening.

Our study shows that during lengthening, a significant amount of nail bending is appreciated, but it cannot be precisely predicted in any given case. The elastic and plastic deformity within the nail is likely due to a number of factors, including passive muscle tension, dynamic forces during physical therapy, and potentially variable patient compliance with weight-bearing recommendations. We identified a relationship between patient weight per mm of nail diameter and nail bending, though significant case-to-case variation was still present. Previous literature has shown that there is on average 2.4° and up to 9° of nail bend in femoral IM limb lengthening[14]. We believe that this nail bending is the main reason for deviation from what is predicted

TABLE VI Patients with MAD Lateral Shift of More Than 5 mm Characteristics

Patient ID	Preoperative MAD (mm)	Consolidation MAD (mm)	MAD Shift (mm)	Predicted MAD Shift (mm)	Nail Bend (°)	BMI (Preoperative)	Lengthening (cm)
1	0.7	−7	7.7	25	1.8	20.8	3
2	−9.7	−15	5.3	3.19	1.1	31.4	8.7
3	0.7	−6	6.7	37.3	1.2	21.4	2.9
4	5.7	−4	9.7	15.6	3.1	24.8	3.5
5	−0.5	−6	5.5	15.8	0	26.3	5.3
6	3.9	−1.2	5.1	32	1.6	29.3	8.6
7	6	−1.4	7.4	25.3	5	19.3	8.7
8	−1.7	−8	6.3	9.18	1	25.1	6

BMI = body mass index, MAD = mechanical axis deviation.

TABLE VIII Linear Regression of the Effect of Weight/Nail Diameter on Nail Bend

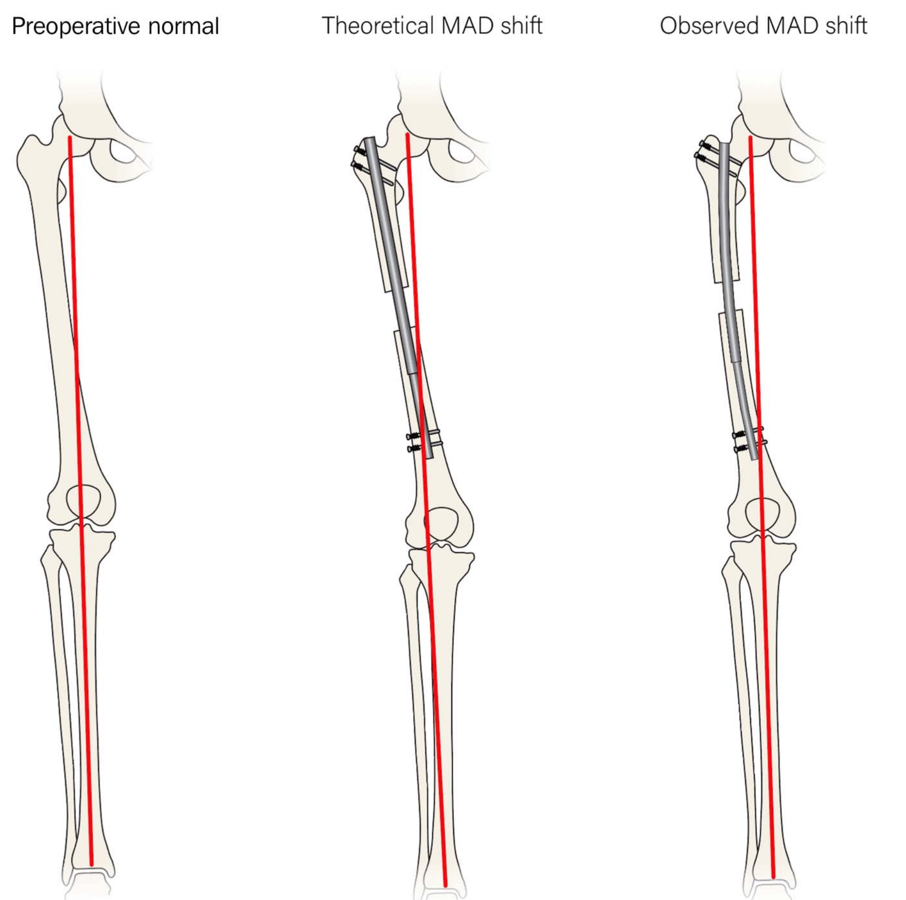
	Dependent Variable: Nail Bend
Weight (kg)/diameter (mm)	0.312** (0.143)
Constant	0.424 (0.875)
Observations	118
R2	0.039
Adjusted R2	0.031
Residual Std. Error	2.129 (df = 116)
F Statistic	4.768** (df = 1; 116)

**p < 0.05.

based on modeling of lengthening along the anatomic, instead of mechanical, axis.

Furthermore, our AMA decreased but was still in the reference range, and no changes in mechanical lateral proximal femoral angle, mLDFA, mMPTA, and mLDTA were appreciated in between the phases of the study. These results strengthen our hypothesis that, on average, no predictable MAD nor significant joint alignment disturbance occurs after MILN without performing any corrective maneuver such as the ones described by Baumgart et al[8,11]. None of the radiographic measurements were significantly correlated with MAD shift, as presented in Table VII.

Our results indicated minimal to no impact on the mechanical axis or the joint alignment of the lower limb after limb lengthening using a femoral MILN in a deformity-free lower limb when averaged across a large patient cohort. All procedures were done without any pre-emptive corrective maneuvers or using any preoperative measures to extrapolate mechanical alignment postlengthening. As observed, no preoperative radiographic markers were significant enough to predict postoperative MAD shift. That being said, the shift is on average, and in the vast majority of cases, too small to be clinically significant. For these reasons, we conclude that there is no need for pre-emptive preoperative



[redacted]

Fig. 4
Theoretical vs. observed MAD shift: Illustration showing the effect of nail bend on MAD shift in intramedullary lengthening in contrast to the theoretical MAD shift in lengthening. MAD = mechanical axis deviation.

MAD medialization to counteract the theoretical lateralization postlengthening over the anatomic axis as proposed by Baumgardt et al.[8] in RPM and later on by Burghardt et al. in their cases series[13]. Further studies are needed to understand the types of forces and factors that lead to the stabilization of the MAD, as well as to identify predictive factors for cases of significant deviation that might require alternative techniques. Study limitations include those inherent to retrospective analyses, since our data collection depends on review of charts that were originally not designed to collect data for research. The reasoning for differences in treatment between patients and incomplete follow-up data has the potential to introduce biases. Furthermore, our study did not discuss ethnic or racial differences in our cohort; this will potentially affect the generalizability of our results. Finally, this is a single-center study and more comprehensive work needs to be done to support widespread changes in practice. ■

Akram Al Ramlawi, MD[1]
Philip K. McClure, MD[1]
John E. Herzenberg, MD[1]
Michael Assayag, MD[1]

[1]International Center for Limb lengthening, Sinai of Baltimore, Baltimore, MD

E-mail address for A. Al Ramlawi: akram.ramlawi@gmail.com

References

1. Hosny GA. Limb lengthening history, evolution, complications and current concepts. J Orthop Traumatol. 2020;21(1):3.

2. Frommer A, Roedl R, Gosheger G, Niemann M, Turkowski D, Toporowski G, Theil C, Laufer A, Vogt B. What are the potential benefits and risks of using magnetically driven antegrade intramedullary lengthening nails for femoral lengthening to treat leg length discrepancy? Clin Orthop Relat Res. 2022;480(4):790-803.

3. Popkov A, Foster P, Gubin A, Borzunov D, Popkov D. The use of flexible intramedullary nails in limb lengthening. Expert Rev Med Devices. 2017;14(9):741-53.

4. Accadbled F, Pailhé R, Cavaignac E, Sales de Gauzy J. Bone lengthening using the Fitbone motorized intramedullary nail: the first experience in France. Orthop Traumatol Surg Res OTSR. 2016;102(2):217-22.

5. FitboneTM intramedullary limb-lengthening system. Limbhealing. Available at: https://limbhealing.com/fitbone/. Accessed May 24, 2024.

6. Paley D. PRECICE intramedullary limb lengthening system. Expert Rev Med Devices. 2015;12(3):231-49.

7. Emara KM, Mahmoud AN, Emara AK, Emara MK. Effect of lengthening along the anatomical axis of the femur and its clinical impact. World J Orthop. 2017;8(5):431-5.

8. Baumgart R. The reverse planning method for lengthening of the lower limb using a straight intramedullary nail with or without deformity correction. A new method. Oper Orthop Traumatol. 2009;21(2):221-33.

9. Hung AL-H, McClure PK, Franzone JM, Hammouda AI, Standard SC, Chau W-W, Herzenberg JE. Bone Ninja mobile app for reverse planning method in internal limb deformity and lengthening surgery. Strateg Trauma Limb Reconstr. 2019;14(2):72-6.

10. Galal S. The Resolution Axis Method (RAM) for lengthening of the femur with or without associated frontal plane deformity (a new method). Strateg Trauma Limb Reconstr. 2018;13(2):109-18.

11. Baumgart R, Betz A, Schweiberer L. A fully implantable motorized intramedullary nail for limb lengthening and bone transport. Clin Orthop Relat Res. 1997;343:135-43.

12. Paley D, Herzenberg JE, Paremain G, Bhave A. Femoral lengthening over an intramedullary nail. A matched-case comparison with Ilizarov femoral lengthening. J Bone Joint Surg Am. 1997;79(10):1464-80.

13. Burghardt RD, Paley D, Specht SC, Herzenberg JE. The effect on mechanical axis deviation of femoral lengthening with an intramedullary telescopic nail. J Bone Joint Surg Br. 2012;94(9):1241-5.

14. Al Ramlawi A, Assayag M, McClure P. PRECICE nail bending in femur lengthening. J Orthop. 2024;56:127-32.