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# A Comparison of the Complications and Effectiveness of Intramedullary Limb Lengthening – A Matched Pair Analysis of Two Different Lengthening Systems (FITBONE®, PRECICE®)

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# 1. Abstract

**Introduction:** Intramedullary limb lengthening to correct congenital or acquired length discrepancy has become a generally accepted concept in reconstructive surgery, but as yet comparative clinical studies are missing, we compared the complications and effectiveness of two types of intramedullary limb lengthening apparatuses.

**Patients and Methods:** In a retrospective series of 303 consecutive patients with internal limb lengthening, we identified 19 matching pairs in terms of predetermined matching parameters (Group A with PRECICE® nail, Group B with Fitbone® nail). All surgeries underwent the same technique and every case implemented equivalent pre- and post-operative treatment in patient management.

The performance of different implants was estimated by using distraction distance (mm) Distraction Index (DI: quotient between the distraction distance and distraction time (mm/d)), Weight Bearing Index (WBI: quotient from time between the surgery to full weight bearing and distraction distance (d/cm)) and Consolidation Index (CI: quotient from time between surgery to radiological consolidation and distraction distance (d/mm)). Complications were evaluated according to Lee's classification system for intramedullary lengthening nails.

**Results:** 19 PRECICE® nail patients (Group A) could successfully be matched to 19 Fitbone® nail (Group B) out of 241 Fitbone® nail patients, according to the five aforementioned criteria (1. Equivalent surgical technique and pre- and post-operative treatment protocol; 2. Location of the osteotomy; 3. Simultaneous realignment of the mechanical axis; 4. maximum variation 20% of the lengthening; 5. maximum variation 20% of age).

The average age of Group A is 25.7yrs (15-43yrs), The average age of Group B is 25yrs (16-40yrs); the average lengthening in Group A is 34.3mm (20-60mm), and the average lengthening in Group B is 34.1mm (23-55mm). The follow-up of all matched cases averaged 29.5months (14-48months). Viewed separately, the follow-up for the PRECICE® group was 29.5months (16-48months) and for the Fitbone® group 29.4months (14 – 42months).

The mean value of Distraction Index in Group A was 0.8mm/d (range: 0.3-1.0 mm/d), and the mean value of Distraction Index in Group B was 0.7mm/d (range:0.2-0.9 mm/d); the mean value of WBI between Group A and Group B differs from 37.7 d/cm (Range: 18.3-62.9 d/cm)

to 47.5 d/cm (Range: 20.4-80.7 d/cm); the average value of CI in Group A is 4.8 d/mm (Range: 2.3-9.7 d/mm), as to Group B is 6.9 d/mm (Range: 5.2-9.4 d/mm).

The results of paired t-test showed that the DI of Group A was higher than that of Group B, The WBI of Group A was lower than that of Group B, The CI of Group A was lower than that of Group B, all three parameters has statistically significant differences ($p < 0.05$).

By subgrouping the osteotomy sites into proximal femur, distal femur and proximal tibia, we found there were no statistically significant differences among three osteotomy site groups, the *p*-values of DI、WBI and CI are all bigger than 0.05. After categorizing the patients according to three diagnoses (congenital, acquired and posttraumatic), finding out there were no significant differences of PRECICE® and Fitbone® nail patients in DI, WBI and CI among three diagnostic groups. (Both $p > 0.05$)

According to Lee's complication system, "Problems" are all unexpected events that can be resolved without surgical intervention. Examples include the formation of a pointed foot that requires physiotherapy treatment. "Obstacles" are incidents that result in one or more surgical interventions, but at the most delay the completion of the treatment and do not endanger the treatment goal. For example, insufficient callus formation, which requires a bone grafting or a re-osteotomy due to premature consolidation of the regenerate. "Sequela" is used in the subsection instead of complications to avoid misunderstanding, which means that results in residual damage after treatment, which lead to the planned distraction distance being missed by more than 10 mm, as well as e.g. an infection of foreign material.

There were 8 recorded problems, 4 recorded obstacles and no sequela in Group A patients, and for Group B patients, there were 9 recorded problems, 4 recorded obstacle and no sequela in both matching patients.

**Conclusions:** Specific technical handicaps of the two systems, such as the so-called magnet operated PRECICE® nail and backtracking of the Fitbone® nail seem to bring about the differences in DI, WBI and CI. Aetiology and osteotomy site did not influence as much as the nail differences according to the results of this study. Further comparative studies might engender technical progress and perfection in intramedullary limb lengthening.

# 2. Zusammenfassung

**Einleitung:** Die intramedulläre Gliedmaßenverlängerung zur Korrektur angeborener oder erworbener Längendifferenz hat sich in der rekonstruktiven Chirurgie zu einem allgemein akzeptierten Konzept entwickelt. Da jedoch noch keine vergleichenden klinischen Studien vorliegen, haben wir die Komplikationen und die Wirksamkeit von zwei Typen intramedullärer Verlängerungsmarknägel verglichen.

**Patienten und Methoden**: In einer retrospektiven Serie von 303 aufeinanderfolgenden Patienten mit innerer Gliedmaßenverlängerung konnten wir 19 Paare in Bezug auf vorbestimmte passende Parameter (Gruppe A mit PRECICE®-Nagel, Gruppe B mit FITBONE®-Nagel) matchen. Alle Eingriffe wurden mit der gleichen Vorbereitung und Technik durchgeführt und in jedem Fall wurde eine gleichwertige prä- und postoperative Behandlung durchgeführt.

Die Leistung von verschiedenen Implantaten wurde anhand des Distraktionsstrecke(mm), des Distraktion Index (DI: Quotient aus Distraktionsstrecke und der Distraktions-Zeit (mm/d)), Weight Bearing Index (WBI: Quotient aus Zeit zwischen Operation bis Vollbelastung und Distraktions-Strecke (d/cm)) und Consolidation Index (CI: Quotient aus Zeit zwischen Operation bis radiologischer Konsolidierung und Distraktions-Strecke(d/mm)) geschätzt. Komplikationen wurden nach Lee´s Klassifikation für die intramedulläre Nagelverlängerung bewertet.

**Ergebnisse:** 19 PRECICE® Nagel-Patienten (Gruppe A) können nach den fünf vorgegebenen Kriterien (1. Äquivalente Operationstechnik und prä- und postoperatives Behandlungsprotokoll; 2. Ort der Osteotomie; 3. Gleichzeitige Neuausrichtung der mechanischen Achse; 4. maximale Variation 20% der Verlängerung; 5. maximale Variation 20% des Alters) erfolgreich mit 19 FITBONE® Nagel (Gruppe B) von 241 Fitbone® Nagel-Patienten abgeglichen werden.

Das Durchschnittsalter der Gruppe A beträgt 25,7 Jahre (15-43 Jahre). Das Durchschnittsalter der Gruppe B beträgt 25,0 Jahre (16-40 Jahre). Die durchschnittliche Distraktionsstrecke beträgt in Gruppe A 34,3 mm (20-60 mm) und in Gruppe B 34,1 mm (23-55 mm). Das Follow-Up aller übereinstimmenden Fälle beträgt durchschnittlich 29,5 Monate (14-48 Monate). Separat betrachtet beträgt das Follow-Up für die PRECICE®-Gruppe 29,5 Monate (16-48 Monate) und für die Fitbone®-Gruppe 29,3 Monate (14 - 42 Monate).

Der Mittelwert von DI ist in Gruppe A 0,79 mm/d (Bereich: 0,30 bis 0,97 mm/d) in Gruppe B ist 0,67 mm/d (Bereich: 0,23 bis 0,91 mm/d). Der Mittelwert des WBI zwischen Gruppe A und Gruppe B unterscheidet sich von 37,7 d / cm (Bereich: 18,3-62,9 d/cm) bis 47,5 d / cm (Bereich: 20,3-80,7 d/cm); Der Durchschnittswert von CI in Gruppe A ist 4,8 d/mm (Bereich: 2,34 bis 9,71 d/mm), während für Gruppe B 6,87 d/mm (Bereich: 5,16 bis 9,44 d/mm) gilt. Die Ergebnisse des gepaarten t-Tests zeigen, dass der DI von Gruppe A höher war als der von Gruppe B, der WBI von Gruppe A niedriger als der von Gruppe B, der CI von Gruppe A niedriger als der von Gruppe B, und alle drei Parameter weisen statistisch signifikante Unterschiede auf ($p < 0{,}05$).

Bei der Untergruppierung der Lokalisation der Osteotomien in proximales Femur, distales Femur und proximale Tibia fanden sich keine statistisch signifikanten Unterschiede zwischen drei Lokalisationen. Die *p*-Werte von DI, WBI und CI sind alle größer als 0,05. Nach Kategorisierung der Patienten nach drei Diagnosen (angeboren, erworben und posttraumatisch längen Differenz) ergab sich kein signifikanter Unterschied zwischen PRECICE®- und Fitbone®-Nagelpatienten bei DI, WBI und CI zwischen drei Diagnosegruppen. (beide $p < 0{,}05$)

Die Auswertung der Komplikationen und Probleme nach Lee's Klassifikation „Probleme" sind alle unerwarteten Ereignisse, die ohne chirurgischen Eingriff behoben werden können. Beispiele hierfür sind die Bildung eines spitzen Fußes, der eine physiotherapeutische Behandlung erfordert. „Hindernisse" sind Vorfälle, die zu einem oder mehreren chirurgischen Eingriffen führen, jedoch den Abschluß der Behandlung höchstens verzögern und das Behandlungsziel nicht gefährden. Zum Beispiel unzureichende Kallus Bildung, die eine Knochentransplantation oder eine Reosteotomie aufgrund einer vorzeitigen Konsolidierung des Regenerats erfordert. „Weiteren Folgen" bedeutet, dass nach der Behandlung Restschäden auftreten, die dazu führen, dass der geplante Distraktionsabstand um mehr als 10 mm verfehlt wird, z. eine Infektion mit Fremdmaterial.

Es gab 8 aufgezeichnete „Probleme", 4 aufgezeichnete „Hindernisse" und keine „weiteren Folgen" bei Patienten der Gruppe A. Und bei Patienten der Gruppe B gab es 9 aufgezeichnete „Probleme", 4 aufgezeichnete „Hindernisse" und ebenso keine „weiteren Folgen".

**Fazit:** Spezifische technische Nachteile der beiden Systeme, wie ein gelegentliches, unkontrolliertes Rücklaufen des Fitbone®-Nagels, scheinen die Unterschiede in DI, WBI und CI hervorzurufen. Die Ätiologie der Beinlängendifferenzen und die Lokalisation der

Osteotomie verursachen keine signifikanten Unterschiede im Ergebnis der beiden Implantate. Weitere, größere klinische Vergleichsstudien könnten zu technischem Fortschritt und weiterer Perfektionierung bei der intramedullären Gliedmaßenverlängerung führen.

# 3. Introduction

## 3.1 Anisomelia

Anisomelia, which is commonly titled as lower limb-length discrepancy (LLD), is describing a pathological situation in which the paired lower limbs have significant inequality.[1] LLD is a common problem that can influence adequate to 90% of the population.[2,3] The ratio between males and females is 1.95:1.[4,5] The pathology classification of LLD is the true LLD and functional LLD,[2] and the true LLD means there is a physical asymmetry of the bone structure existing someplace extending from the head of the femur to the ankle mortise, on the other hand, the functional LLD is because of the changed mechanics, which affects the body to have a physiological reaction accordingly, targeting from the lumber spine to the foot and causing the condition of short leg with or without actual bony asymmetry. However, no matter which kind of the LLD, the kinetic chain is always under the influence and needed to be treated. The etiology of the LLD can be divided into three groups: congenital LLD, such as malformation, bone growth disorder, the acquired LLD, such as infection, and polio, and posttraumatic LLD, such as car-accident.[6]

LLD can contribute to standing imbalance, low back pain,[7] associated running injuries, osteoarthritis, forces transmitted through the hip,[8] aseptic loosening of the prosthesis, stress fracture[9] and so on. When it comes to the boundary between acceptable lower limb discrepancy, which should not be considered to be a problem or affect too much of the life quality as an

1. Giles LG, 1981 „Lower-back pain associated with leg length inequality “.

2. Woerman AL, 1984 „Leg Length discrepancy Assessment: Accuracy and Precision in Five Clinical Methods of Evaluation “.

3. Maffulli N, 2010 „Sports injuries in young athletes: long-term outcome and prevention strategies “.

4. Guichet JM, 1991 „Lower limb-length discrepancy. An epidemiologic study “.

5. Raczkowski JW, 2010 „Clinical research Functional scoliosis caused by leg length discrepancy “.

6. Gurney B, 2002 „ Leg Length Discrepancy “.

7. Sheha ED, 2018 „ Leg-Length Discrepancy, Functional Scoliosis, and Low Back Pain “.

8. Visuri T, 1993 „ The role of overlength of the leg in aseptic loosening after total hip arthroplasty “.

9. Brand RA, 1996 „ Effects of leg length discrepancies on the forces at the hip joint “.

individual, and a certain point when surgical intervention is necessary, there always exists a controversial debate. From Gross's study in 1978,[10] more than 2 cm discrepancy of the lower limb should be considered as the cut-off point, but clinical judgment should still be made on the patient basis, and Reid's research[11] in 1984 suggested to divided LLD patients into three kinds: 0-30mm classified as mild, which should not be treated or treat with non-surgical methods such as shoe insoles, 30-60mm classified as moderate, in which clinical judgment should still be made on the patient basis, but surgical treatment is recommended, the most severe category is >60mm, which definitely needs surgical intervention.

Before treatment, the patient needs to go through a comprehensive clinical examination including range of motion, stability of joints and precise measurement of the leg length discrepancy by placing blocks beneath the foot of the shorter leg. The equality in the leg length is observed via pelvic and vertical spine. All of these need to be done before radiologic assessment.

Until now, several radiologic assessment methods were implemented, for example, using only standard knee x-ray, which is still very controversial, because the whole lower limb mechanics are missing from the short X-rays, and over- or under- correction will surely lead to unsatisfactory outcomes, using only MRI, CT or computer-assisted navigation system cannot reveal the lower limb mechanics with truly full weight bearing results,[12] and thanks to the development of the technology, currently we have the weight bearing CT scans and EOS X-ray imaging system. However, considering cost performance, time-consuming, universal approach, and truly full weight bearing, long standing radiograph (LSR) is sufficient enough to provide reliable results and easy access, because a LSR should include the hip, knee and the ankle with a centred patella, which provides the possibility to define and measure lower limb alignment in the frontal plane and determine the individual deformity within femur and tibia. Hence, becoming the mainstream in daily practice and the golden standard.[13] After combining radiologic results with clinical examinations, if the patient needs surgical treatment, meticulous

10. Gross RH, 1978 „ Leg length discrepancy: how much is too much ".

11. Reid DC, 1984 „ Leg length inequality: a review of etiology and management ".

12. Dexel J, 2014 „ Agreement between radiological and computer navigation measurement of lower limb alignment. Knee Surgery ".

13. Babazadeh S, 2013 „ The long leg radiograph is a reliable method of assessing alignment when compared to computer-assisted navigation and computer tomography ".

pre-operational planning based on LSR should be done for intraoperative control and foreseeable good results.

There are two main kinds of treatments for patients who have an LLD: non-operative and operative way. The non-operative treatment includes shoe lift and observation-only, and the LLD＜2cm and without back pain, scoliosis, or other complaints should be good indications for inclusion. The operative treatment includes shortening of the longer side by epiphysiodesis of the tibia, femur or both, periosteal circumcision, physeal bar excision, even amputation and prosthetic fitting in severe cases, and limb lengthening or distraction osteogenesis of the shorter leg, which is considered to be the first choice for most patients who need surgical intervention. Moreover, for the lengthening surgery, two kinds of tools (external fixation system and intramedullary nailing system) will be mentioned afterward.[14,15]

### 3.2 Distraction Osteogenesis by External Fixation

Distraction osteogenesis by external fixation is a world-wide established method for treating orthopaedic extremity deformity, which has been put into clinical treatment since the early 1900s,[16] The treatment of using external fixation involves pins, wires, clamps and stable rings, which is also associated with a plethora of complications, well-known as pin-tract infection,[17] pain during lengthening,[18] muscle contractures caused by the tension generated by distraction, [19] soft-tissue trans fixation, possible neurovascular damage,[20] dislocation of the ankle and hip, joint stiffness, the cumbersome external fixator which needs persistent maintenance, and long-term wearing of the external fixation can also be the cause of the loss of appetite and depression of the patients.[21] The new technique of coupling internal and external fixation (hybrid

14. Stanitski DF, 1999,, Limb-Length Inequality: Assessment and Treatment Options ".

15. Jorge GA. 1992,, Delayed distraction in bone lengthening ".

16. Moss DP, 2007,, Biomechanics of external fixation: a review of the literature ".

17. Jauregui JJ, 2015,, Life- and limb-threatening infections following the use of an external fixator ".

18. Eralp L, 2007,, Distal Tibial Reconstruction with Use of a Circular External Fixator and an Intramedullary Nail ".

19. Paley D, 1990,, Mechanical evaluation of external fixators used in limb lengthening ".

20. Kristiansen LP, 1999,, Lengthening of the tibia over an intramedullary nail, using the llizarov external fixator: Major complications and slow consolidation in 9 lengthenings ".

21. Wang Y, 2017,, Comparison of Monolateral External Fixation and internal Fixation for Skeletal Stabilization in the Management of Small Tibial Bone Defects following Successful Treatment of Chronic Osteomyelitis ".

techniques) such as lengthening and plating, lengthening over nailing and lengthening and then nailing can reduce the span of wearing the external fixator.[22] Nevertheless, all of these new ideas cannot avoid or address related complications of the external fixation. However, when dealing with a severe case of complicated lower limb bone reconstruction, compared with internal fixation, external fixation has the priority, because it has the advantage of independence from the excellent condition of bone quality, multi planar correction, or the existence of active infection or osteomyelitis.[23]

### 3.3 Fully Implantable Intramedullary Nails

In order to eliminate or at least reduce the potential complications caused by external fixation, the development of a fully intramedullary lengthening apparatus has proceeded. When comparing with external fixator, intramedullary lengthening nail has several superiorities in the management of the leg length discrepancies, such as lower infection rates, less soft tissue damage and pain, better joint movement, better alignment control, and much lower maintenance.[24,25]

Over the past years, seven different fully implantable internal lengthening devices have been developed and studied in the literature to obviate the need for external fixation, including the first intramedullary apparatus used for distraction osteogenesis (Bliskunov® nail)[26] with very few existing researches; Albizzia® nail (Medinov-AMP, Roanne, France)[27] produced in the early 1990s, and its further developmental mode which is called Betzbone® nail or Guichet nail(Med-Tech GbmH-Betz Institute Wadern, Deutschland) by its two names.[28] The Phenix® nail (Soubeiran, France)[29] is magnetic driven system; the Bliskunov® Nail, the Albizza® Nail

22. Mahboubian S, 2012 „ Femoral Lengthening with Lengthening over a Nail has Fewer Complications than Intramedullary Skeletal Kinetic Distraction “.

23. Lee DJ, 2016 „ Internal versus External Fixation of Charcot Midfoot Deformity Realignment “.

24. AL-Sayyad MJ, 2012 „ Lower limb lengthening and deformity correction using the Fitbone motorized nail system in the adolescent patient “.

25. Guichet JM, 2003 „ Gradual femoral lengthening with the albizzia intramedullary nail “.

26. Bliskunov AI, 1983 „ Intramedullary distraction of the femur (preliminary report) “.

27. Mazeau P, 2012 „ Complications of Albizzia femoral lengthening nail: an analysis of 36 cases “.

28. Weber P, 2017„Ausgleich posttraumatischer Beinlängendifferenzen mit einem Verlängerungsmarknagel “.

29. Thaller PH, 2014 „ Limb lengthening with fully implantable magnetically actuated mechanical nails (PHENIX (®))-Preliminary results “.

are driven by mechanical ratchet system. All of those three above nails are currently off the market. The Intramedullary Skeletal Kinetic Distractor (ISKD®, Orthofix Mckinney) is actuated by two rotational ratcheting clutches between the housing and the telescoping section,[30] which means that it requires fewer degrees of rotation than Bliskunov and Albizzia to motivate and elongate the device, the mechanism sounds much more efficient and costs less effort, indeed, this has proven to be the obvious problematic part combining with unexpected accelerated lengthening, easily jammed or non-distracting that leads to early consolidation, the absence of reliable control regarding to lengthening and speed happens frequently enough to let the company withdraw it from the market in 2009,[30] and right now ISKD® nail is once again available in Europe.[30,31,32,33] Hence the market has been dominated by Fitbone® nail and PRECICE® nail in the last decades, which will be introduced in detail below, the re-occurrence of the ISKD® Nail does not seem clear.

### 3.4 The Introduction of Fitbone® Nail

The Fitbone® nail was invented at our clinic in 1990.[34] It is an electrically driven system, which means the power of the actuation is delivered from an external controller to a subcutaneous receiver, the subcutaneous receiver is linked to the electric motor system inside the nail through a cord. Telescope Active Actuator (TAA) and Sliding Active Actuator (SAA) are the two types of the nails with two completely different actuation mechanisms. TAA is telescoping and pushing, and SAA is only pulling. Between the two kinds of the nails, TAA is more frequently clinical used, because the lengthening is happening by the telescoping distal part of the nail via a threaded rod, which extends or pushes telescopically, and available both in femur and tibia. On the other hand, the SAA nail is rarely applied because: 1) A minimum diameter of 13mm; 2) Only antegrade femoral insertion; 3) SAA nail pulls the proximal part of the nail distally into the bone, which has been fixed by a screw, going on into a slotted sliding hole (up to 8 cm of

30. Burghardt RD, 2011 „ Mechanical failure of the intramedullary skeletal kinetic distractor in limb lengthening “.

31. Cole JD, 2001 „ The intramedullary skeletal kinetic distractor (ISKD): first clinical results of a new intramedullary nail for lengthening of the femur and tibia “.

32. Kenawey M, 2011 „ Leg lengthening using intramedullary skeletal kinetic distractor: Results of 57 consecutive applications “.

33. Lee DH, 2014 „ Complications of the Intramedullary Skeletal Kinetic Distractor (ISKD) in Distraction Osteogenesis “.

34. Betz A, 1990 „ First fully implantable intramedullary system for callus distraction--intramedullary nail with programmable drive for leg lengthening and segment displacement “.

stroke) which causes stability problems of the implant; 4) The process of lengthening will occupy space of the distal femur. But in a modified version, it allows bone transport.

The complication rate of Fitbone® nail differs from 12.5% to 15.4% in various studies,[35,36] and from the studies, we could know that a controlled and progressive lengthening procedure will definitely lower the complication rate. The range of healing index for Fitbone® nail is 48 days/cm to 26 days/cm. Technical complications or implant breakage are rarely reported with Fitbone® nail; the most commonly reported is the loss of elongation due to either loose locking screw or running back of the telescoping part. The new version of the Fitbone® nail has developed a barrier, to prevent this so-called backtracking.[37]

### 3.5 The Introduction of PRECICE® Nail

The PRECICE® (Ellipse Technologies Inc., CA, USA) intramedullary limb lengthening system is a magnet-driven telescopic internal lengthening apparatus, which has both US FDA clearance and CE mark for their first two-generation system.[38] The first surgery with PRECICE® nail had been operated in May 2011 without published evidence of follow-up. The earliest available publication was from Rozbruch and Hamdy's book, [39] according to this and to the best of our knowledge, the 2nd PRECICE® nail surgery was performed with good final result by Metin küçükkaya in June 2011 in Istanbul. The PRECICE® nail constitutes a thin magnetic metal spindle with four sections (magnet section, gearing section, retainer section and anti-jam section). It is actuated by an external remote controller (ERC), which combines with two rotating magnets that can rotate the magnetic spindle in both directions (lengthening and shortening) and allows precise distraction at a defined speed. Applying the ERC in one direction elongates, and the other way around, it shortens.

35. Accadbled F, 2016 „ Bone lengthening using the Fitbone ® motorized intramedullary nail: The first experience in France “.

36. Baumgart R, 2006 „ A Fully Implantable, Programmable Distraction Nail (Fitbone) — New Perspectives for Corrective and Reconstructive Limb Surgery “.

37. Krieg AH, 2011 „ Intramedullary leg lengthening with a motorized nail: Indications, challenges, and outcome in 32 patients “.

38. Paley D, 2015 „ PRECICE intramedullary limb lengthening system “.

39 Rozbruch SR, 2015 „ Limb lengthening and reconstruction surgery case atlas “.

The complication rate of PRECICE® nail differs from 11.5% to 13% in various studies.[40,41] According to Wagner's study,[41] the healing index of PRECICE® nail patients is similar to Fitbone® nail patients. In 2011, the first generation of PRECICE nail® (P1) was produced, but because of the design of the thin magnetic metal spindle and the comparatively fragile parts (crown and fins), which located in the anti-rotation mechanism of the nail, the most reported[38, 40, 41] complication associated with the PRECICE® nail itself is the breakage or the bowing. The company had decided to modify the nail accordingly with their second generation of PRECICE® nail in 2012 (P2) and in 2014 (P2.1) with much more robust device. In 2018, the company had launched the third generation called PRECICE® STRYDE, which was recently cleared by US FDA and allowed immediate full weight-bearing after an operation, but still has limited resources and so far, no clinical research was found except a few single cases reported by the company online.

# 4. Aim of the Study

Up to now, our team was able to gain enough experience with five different, fully internal implanted lengthening devices.[42] There are tons of multiple pieces of literature of specific case series concerning external fixations and other internal lengthening systems.[18,20,26,32,35,43] A scientific evaluation between the intramedullary lengthening systems is difficult as the number of implantations is inadequate globally, and techniques vary significantly among surgeons. To

40. Nasto LA, 2020 „ Clinical results and complication rates of lower limb lengthening in pediatric patients using the PRECICE 2 intramedullary magnetic nail: a multicenter study ".

41. Wagner P, 2017 „ PRECICE ® magnetically-driven, telescopic, intramedullary lengthening nail: pre-clinical testing and first 30 patients ".

42. Thaller PH, 2017 „Längen-, Achs- und Torsionskorrekturen mit Distraktionsmarknägeln: Erfahrungen mit 5 verschiedenen Systemen ".

43. Li P, 2019 „ External fixation-assisted reduction for the treatment of neglected hip dislocations with limb length discrepancy: a retrospective study of 13 cases ".

our knowledge so far, we have found nine[44,45,46,47,48,49,50,51,52] matched pair literatures of lengthening over nail comparing with traditional external lengthening system (Ilizarov) and about lengthening nails versus traditional external lengthening system (Ilizarov). All the matched studies we have found is somehow related to external fixation and using Paley's classification system[53] exclusively designed for external devices. However, right now, there are no matched pair studies that were comparing specific intramedullary lengthening apparatus adopting intramedullary lengthening classification system.[54]

This study is the first matched-pair analysis comparing two currently dominant intramedullary lengthening systems (PRECICE® and Fitbone®) using Lee's new intramedullary lengthening classification system.

# 5. Patients and Methods

## 5.1 Matching Criteria

All matched pairs must conform to the agreement in five criteria:

1) Equivalent surgical technique and pre- and post-operative treatment protocol
2) Site of osteotomy (proximal femur, distal femur or proximal tibia)
3) Simultaneous realignment of the mechanical axis (yes or no)

44. Paley D, 1997 „ Femoral lengthening over an intramedullary nail: a matched-case comparison with Ilizarov femoral lengthening ".

45. Salcedo CC, 2018 „ Tibial bone lengthening via external fixation: Comparative study of the traditional technique and a technique with intramedullary nail assistance ".

46. Xu W, 2017 „ Comparison of Intramedullary Nail versus Conventional Ilizarov Method for Lower Limb Lengthening: A Systematic Review and Meta-Analysis ".

47. Fragomen AT, 2018 „ A Comparison of Femoral Lengthening Methods Favors the Magnetic Internal Lengthening Nail When Compared with Lengthening Over a Nail ".

48. Sun XT, 2011 „ Complications and outcome of Tibial lengthening using the Ilizarov method with or without a supplementary intramedullary nail: A CASE-MATCHED COMPARATIVE STUDY ".

49. Guo Q, 2012 „ Tibial lengthening over an intramedullary nail in patients with short stature or leg-length discrepancy: a comparative study ".

50. Burghardt RD, 2016 „ Tibial lengthening over intramedullary nails: A matched case comparison with Ilizarov Tibial lengthening ".

51. Horn J, 2015 „ Femoral lengthening with a motorized intramedullary nail: A matched-pair comparison with external ring fixator lengthening in 30 cases ".

52. Rozbruch SR, 2008 „ Limb Lengthening and Then Insertion of an Intramedullary Nail: A Case-matched Comparison ".

53. Paley D, 1990 „ Problems, obstacles, and complications of limb lengthening by the Ilizarov technique ".

54. Lee DH, 2017 „ A Comparison of the Device-Related Complications of Intramedullary Lengthening Nails Using a New Classification System ".

4) Amount of lengthening (maximal variation 20%)
5) Age (maximal variation 20%)

The following criteria led to the exclusion of the study:

1) Simultaneous elongation of two bones in one patient
2) Implant failure due to a fall or misconduct by the patient
3) The consumption of nicotine during the treatment period
4) Patients who had not finished the whole procedure of lengthening

All five criteria had to comply with both matching pairs. Implant failure due to the malpractice by the patient or accidental trauma, or nicotine abuse during lengthening led to exclusion. Mismatching in gender and etiology of the leg length discrepancy were not included in the matching criteria but will be recorded in the data collection.

## 5.2 Patients Collection

In the retrospective review of a consecutive series, we have found 303 patients who had lengthening of the lower limb using the two intramedullary lengthening system (PRECICE® and Fitbone® nail) between March 1999 and January 2018. We performed 241 limb lengthening procedures with an internal implantable electromechanical-actuated intramedullary nail (Fitbone® nail). From July 2012 to January 2018, 62 consecutive limb-lengthening procedures were performed using a fully implantable magnetic-actuated intramedullary nail (PRECICE® nail). All procedures were performed by the same surgeon (Dr. Peter H. Thaller) with an equivalent technique (see below).

## 5.3 Paring of the Patients

Initially, the cases from PRECICE® nail group were all examined for the possible exclusion criteria. Five of them have lost the final protocol examinations, and nine of them have simultaneously lengthening, and one with humeral lengthening. The most appropriate pairing in the Fitbone® nail group was sought for the remaining 47 PRECICE® nail patients. For this purpose, the cases after the localization of the osteotomy were divided into three groups. Within these groups, the cases were sorted according to the distraction distance. For each PRECICE®

nail patient with the same osteotomy site, a partner with the same distraction distance was sought, in whom the age at the time of the implantation deviated least, but at most by 20%, from the age of the PRECICE® nail patient at the time of implantation, If there was no case with a matching distraction distance in the Fitbone® patients, partners with the least deviating distraction distance were sought. This could be both longer and shorter but had to be within the 20% required by the matching criteria. In cases with the same difference in length and age, cases later in the operation date were preferred, if their parameters matched, the selected Fitbone® case was checked according to the same criteria as the PRECICE® nail cases. Following this procedure, 19 comparable Fitbone® nail patients could be matched to 19 PRECICE® nail patients.

## 5.4 Pre-operational Preparations

### 5.4.1 Clinical Evaluation and Patients

When engaging the patients who are willing to continue the process of limb lengthening in the outpatient department, we could get the information of the etiology and history concerning the limb length discrepancy from the patient, then we need to do an overall preparative specialist physical examinations: if the patient has the manifestation of any kind of joint contractures, how about their joint range of motion (ROM), if the patient has any indication of unstable joints. Torsional deformation should also be considered in the process. (Fig.1) In order to understand and have better control of the further recovery of the lengthening, it is essential to check the patient's vascular, neurological performance or conditions, and standard laboratory examinations such as infection and coagulation parameters. Other minor risk factors such as smoking history, poor nutrition, Body Mass Index > 30kg/m$^2$, and age need to be noticed by physicians.[55]

### 5.4.2 Radiologic Assessment

After the meticulous clinical examinations of the patients, our department's standard requirement for radiologic assessment includes a lateral diagnostic view for the targeted segments of the lower limb, and Long Standing Radiograph x-rays (LSR) (Fig.2).

55. Liantis P, 2014 „Risk factors for and complications of distraction osteogenesis ".

An LSR is a conventional x-ray with both legs, full size in antero-posterior view. The patient is full weight bearing on both legs, fully extended. Both legs are rotated with the patella in the centered position and if needed leg length inequalities are compensated by designated spacer boards. For calibration a 30 mm radiopaque sphere is positioned on the level of the bone between or below the knees. To reduce the magnification, the effective distance between x-ray source and film is 3 meters. An x-ray protector for the gonads is positioned in a way which still visualizes both hip joints.

Full size lateral x-ray views are performed of the femur and/or tibia of interest.

If there is any suspect for a torsional deformity during the physical examinations or in the LSR, a low-dose computed tomography (CT) examination should be carried out for torsional analysis.

### 5.4.3 End Point First Method

After finishing the LSR, in our department, we use a professional graphic software (Corel Draw X4) to analysis the basic and relevant anatomical landmarks[56,57] using the templates that are already created in our department. (Fig.3) The mechanical and anatomical leg axis and lower limb angles described by Paley are measured. (Fig.4) The idea of using anatomical landmarks to define lower limb axes and related angles around the knee in LRS was mainly raised by Moreland in 1987.[58]

In 1879, Mikulicz[59] had first introduced the idea of biomechanical axis of lower limb in the coronal plane, which was named as Mikulicz line (including from the vertex of the femoral head to the midpoint of talocrural joint). In 1992, Paley and Tetsworth[60] presented with the idea of implementing malalignment test, which is based on the idea of regaining normal Mikulicz line, to understand if upper or lower leg contributes to the deformation and to localize the deformed part(s) of the bone the so called “Center(s) Of Rotation and Angulation (CORA). From there, they developed a planning method to even correct the most complex deformities

56.Thaller PH, 2005 „ Digital imaging in lower limb bone deformities–standards and new perspectives “.

57.Thaller PH, 2010 „ Planning of lower deformity correction with professional graphic software “.

58. Moreland JR, 1987 „ Radiographic analysis of the axial alignment of the lower extremity “.

59. Mikulicz J. 1879 „Die seitlichen Verkrümmungen am Knie und deren Heilungsmethoden “.

60. Paley D, 1992 „ Mechanical axis deviation of the lower limbs: preoperative planning of uniapical angular deformities of the tibia or femur “.

mainly with ring fixators according to the Ilizarov Method with osteotomies in or close to this CORA.

At that time like today, a detailed analysis of a scaled LSR is prerequisite for the following digital planning. But nowadays as internal fixation devices have become much more important than external fixation, so there was need for another planning method with more emphasis on the fit and stability of the internal implant than on CORA. This method nowadays called End-Point-First (EPF) method, which is applied in our 3D-Surgery department for more than two decades. It is a versatile planning method for both internal and external implants.

The actual digital EPF planning were all applied with EPF method, the endpoint (EP) of the correction target is first defined by the new Mechanical Axis (nMA). nMA for unifocal corrections is defined by the mechanical axis of the unaffected bone. Since for bifocal corrections both femur and tibia are corrected the refence for the nMA is defined by the knee joint line. In this case the nMA is drawn by projecting the new, normal values of the mechanical lateral distal femoral angle (mLDFA) and/or the medial proximal tibial angle (MPTA) to the existing knee joint line. To define the endpoint for additional length procedures the desired length is simply added on the nMA.

As an example for an unifocal deformity planning, where we want to correct the patient on tibia, then the nMA is defined by the center of the femoral head and the center of the knee, which simulate the desired endpoint of the distal tibia first, thus in the case of a patient with axis correction and lengthening using intramedullary nail, the EPF method will enable the implant into the segment properly, then move the distal compound (cut distal tibia bone and implant nail) to the planned endpoint, finally lengthening the compound along intramedullary nail axis. After that, there will be three statuses created: current status, status after osteotomy and final status with the lengthening goal which has been reached. The contour of the bone to be corrected is marked along the cortex in the digital planning. After defining the osteotomy and adjusting the implant in the medullary canal of the segment to be moved, it can be adjusted from the EP along the medullary nail axis to the osteotomy. The necessary stroke of the implant and assistant angles are preplanned graphically as followed: templates (Fig.5) have been stored in the software for the selection of the suitable length and width of implants in the digital drawing, which can also be easily scaled via the bones that are positioned and selected according to the dimension of the medullary canal, locking options and different kinds of available lengthening nails on the market. All the assistant tools in the digital drawing were produced in our clinic.

The final completion of the planning is served as the guide during the operation on a scale of 1:1. (Fig.6)

## 5.5 Implants

### 5.5.1 Fitbone® Nail® and Experiences

The Fitbone® nail (Fig.7) is electrically driven and developed in our department.[34] The energy is delivered by induction, from an external transmission unit to a subcutaneous receiver, which is connected via a cord to the electric motor system inside the nail. There are two kinds of actuation; one is telescoping and pushing (TAA), which is more frequently used in the clinic, TAA got both femoral and tibia nails, although femoral TAA is designed only for retrograde implantation, but after years' clinical application, we found it feasible to perform antegrade femoral surgeries, which also got very satisfactory results. And the other Fitbone® nail is Sliding Active Actuator (SAA), which is rarely used, (see chapter 1.4) because the distraction takes places at the distal femur at the same place as in retrograde femoral lengthening nails. In 2006, we had already reported on 150 lengthening operations with the Fitbone® nail.[36] In this study, 144 patients had reached the distraction goal, no infection was found, implant failure happened in 3 cases, nine other technical obstacles were reported, and the unintended backtracking happened in 9 patients which were consistent with complications reported by other studies.[34,35,61]

### 5.5.2 PRECICE® Nail and Experiences

The PRECICE® nail (Fig.8) contains a magnet-operated threaded rod that is connected to a gear box. Elongation of the nail is activated by an external remote-control (ERC) device. The two internal revolving magnets interact with ERC. Facing the ERC in one direction causes the nail to lengthen, while facing it the other direction, it would go in the reverse direction(shortening), which is the first intramedullary nail that has bidirectional control (lengthening and shortening), and the distraction processes are recorded in the ERC integrated computer. However, this is not telemetric data, so regular radiological monitoring is still essential for the patients. Nevertheless, the simplicity of operation can be used for an individual adjustment of the distraction speed.

61. Singh S, 2006 „ The results of limb lengthening by callus distraction using an extending intramedullary nail (Fitbone) in non-traumatic disorders ".

Until January 2018, we have treated 62 patients with consecutive lower limb-lengthening procedures using PRECICE® nails, also quite familiar with the management or treatment of the obstacles or complications related to PRECICE® nails such as contractures, delayed callus formation which thus by means of slower distraction speed or intermittent shortening, apparatus dysfunction or breakage of the nails.[42, 62] For example, our first experience dealing with PRECICE® nail breakage was with one young female patient inserted PRECICE® nail (P1) in 2013. The breakage happened during consolidation period, we did successfully remove the broken nail, and replaced it with a solid intramedullary nail to reduce the risk of length loss. All the patients included in this study were treated with the second generation of PRECICE® nails.

With no matter Fitbone® nail or PRECICE® nail, our team both has adequate experiences to confidently perform the operation and deal with the possible complications of its own without any favors, our experiences with both of the nails are not limited only within lower extremities, we have also published our preliminary report concerning the lengthening of the humerus with fully implantable nails (Fitbone® nail and PRECICE® nail).[63]

## 5.6 Surgical Technique

The surgery is carried out on both implants under the intubation anesthesia in the supine position. The planning is hung up on a scale of 1: 1 printout in the operating room. The patient is supine on a planned field with radiopaque lines, which enables intraoperative axis determination using the image converter. The surgical procedure is almost identical for both implants. For operations on the femur, a Schanz pin is placed proximally and distally for better torsion control. The nail´s entry point is marked with a 3mm K-wire using a 20mm incision. A thin-walled steel sleeve is hammered into the bone, and the medullary canal is drilled out with rigid drills until the planned osteotomy. The osteotomies are created minimally invasively as a drill bit osteotomy and completed with a chisel (Fig.9). After the osteotomy, the medullary canal is bored further. The overburden from the drill is saved for later bone grafting in the area of the osteotomy (auto bone grafting). The intramedullary nails are locked via stab incisions, the locking bolts are placed close with a guiding device on the entry portion and by means of a radiolucent, angular gear

62. Thaller PH., 2014,, Surgical Techniques for Lengthening and Deformity Correction of the Tibia with Lengthening Nails “.

63. Fürmetz, J., 2017 „ Lengthening of the humerus with intramedullary lengthening nails—preliminary report “.

drive angular gear on the other portion. A fibula osteotomy is performed for tibia distractions and for distraction distances over 3 cm, the tibia and fibula are transfixed for the lengthening phase using set screws. At the end of the surgery, an alignment re-check is carried out with the help of the planned field (X-Ray Grid Method) (Fig.10), a trial distraction of 1 mm and the accumulation of the cancellous bone at the osteotomy site (auto bone grafting). Depending on the tendency to bleed, a drainage tube is placed at the entry point and, if necessary, at the osteotomies.

## 5.7 Aftercare

After the surgery, patients will be closely looked after with both the Fitbone® and the PRECICE® nail. All patients received low molecular weight heparin, vitamin D, and calcium postoperatively. The analgesia was carried out according to the WHO grading scheme, but without non-steroidal anti-inflammatory drugs (NSAIDs), as these are suspected of negatively influencing bone healing.

From the first postoperative day, patients are mobilized on forearm crutches with a partial bearing of 20 kg. Distraction begins on the morning of the 5th post-operative day. Before discharging the patient, a comprehensive education on the ERC for both kinds of nails and a specific protocol that documents the daily lengthening and pain level should be implemented for patients. Fitbone® nail patients should be educated to place the electronic transmitter to the subcutaneous receiver, and PRECICE® nail patients should be educated to target the position of the magnet in the nails. With PRECICE® nail, special care should also be taken to the direction and application of the ERC. If the distraction is regular (controlled by a focused a.p. x-ray image), discharge is usually on the $8^{th}$ -$10^{th}$ post-operative day. During the distraction phase, weekly, latest by-weekly outpatient checks are carried out. And physiotherapy treatment is assigned close to patient's living address, at least three times a week in the first few weeks. As part of each presentation during outpatient department, a focused a.p. x-ray image of the regenerate is taken in order to measure the distracted distance and to assess the callus formation (Fig.11). The targeted distraction rate is 1 mm/d, but the distraction speed will be adjusted according to radiological results of consolidation in the bony regeneration, movement of the joints, and neurovascular structures.

It is the crucial stage in bone healing and remodeling during consolidation phase. Patients

initially show up in the outpatient at two-week intervals, later at six and twelve weeks. Physiotherapy can be reduced or skipped if the course is regular. In the PRECICE® nail cases there was no backtracking, but the Fitbone® nail cases need particular attention to the return of an already distracted route, which is known as backtracking, and to compensate for it if necessary, until reaches the final length.

The surgeon approves the gradual increase of load until full weight bearing as soon as one cortex, usually the posterior cortex is consolidated enough and no contraindications. After achieving the distraction goal, consolidation was observed every two weeks. When partial consolidation was achieved, the patients come to the clinic every six weeks for radiologic control. When there is radiological evidence of stability, for example, physician observed at least one cortical side of the regenerate. Weight bearing will increase until to the full weight bearing. As part of the full load, the patients can already practice low impact sports. After 12-18 months, the implant is removed during a 1-2 days stay in the hospital. Six months after the removal, a final reassessment of clinical and radiological parameters, such as leg length and alignment, were again managed via LSR. Problems, obstacles and complications were classified throughout the whole treatment phase.

## 5.8 Measure Parameters

Primary measure parameters included full prolongation (mm), distraction index (DI) in mm/d, which was calculated from the length of the radiographic distraction gap divided by the time between beginning to the end of the distraction, weight bearing index (WBI) in d/cm, which was calculated from the duration of operation day to the day of full weight bearing divided by extended length and consolidation index (CI) in d/mm, which was calculated from the interval of the operation date to the date of radiographic consolidation divided by the length of the distraction gap. The radiographic consolidation means the day when three of four cortices were seen to be intact on the anteroposterior and lateral radiographs.(Fig.12) All parameters were described in previous publications[30,33,38,64,65,66] The WBI is not reported in every case series

64. Hankemeier S, 2004 „ Improved comfort in lower limb lengthening with the intramedullary skeletal kinetic distractor “.

65. Schiedel FM, 2014„ How precise is the PRECICE compared to the ISKD in intramedullary limb lengthening? Reliability and safety in 26 procedures “.

66. Leidinger B, 2006„ Limb lengthening with a fully implantable mechanical distraction intramedullary nail “.

concerning intramedullary limb lengthening and is frequently described as the healing index. In the past, the healing index such as WBI and CI, which are always associated with the type of distraction in regard to external versus internal implants. From the definition, we can see that CI, as a parameter, can be very subjective and depend much more on patient medical compliance comparing with WBI.[64,65,66,67] in this study, we decided to record all the indexes to have a comprehensive understanding of both nails.

All the matched-paired literatures[44,45,46,47,48,49,50,51,52] that we have found related to fully implantable nails, all of them have used the Paley's classification system initially described for external lengthening system, [53] but in our study, we used Lee's classification system[54] especially for intramedullary lengthening nails to categorize problems, obstacles and complications.

- **Problems** *are all unexpected events that can be resolved without surgical intervention. Examples include the formation of a pointed foot that requires physiotherapy treatment.*
- **Obstacles** *are incidents that result in one or more surgical interventions, but at the most delay the completion of the treatment and do not endanger the treatment goal. For example, insufficient callus formation, which requires a bone grafting or a re-osteotomy due to premature consolidation of the regenerate.*
- **Sequela** *is used in the subsection instead of complications to avoid misunderstanding, which means that results in residual damage after treatment, which lead to the planned distraction distance being missed by more than 10 mm, as well as e.g. an infection of foreign material.*

## 5.9 Statistics

Using SPSS 25.0, all matched variables were evaluated for statistical significance between groups using a Non-parametric test (Wilcoxon test), *p*-value less than 0.05 was regarded as statistically significant.

67. Thaller PH., 2011,„Comparison between fully implantable motorized and mechanical distraction nails - a matched-pairs study ".

### 5.10 Ethical Approval

Ethical approval to undertake this study was examined from Ethics Committee, Ludwig-Maxilians-Universität München. (Zeichen: 8-16)

### 5.11 Funding

Fuhuan Chen (Award No. 201708610143) received a three-year scholarship from the China Scholarship Council (CSC). The funder was not involved in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

## 6. Results

19 PRECICE® nail patients (Group A) could successfully be matched to 19 Fitbone® nail (Group B) out of 241 Fitbone® nail patients, according to the five aforementioned criteria. The average age of Group A is 25.7yrs (15-43yrs), The average age of Group B is 25yrs (16-40yrs); the average lengthening in Group A is 34.3mm (20-60mm), and the average lengthening in Group B is 34.1mm (23-55mm). (Tab.1) The follow-up of all matched cases averaged 29.5months (14-48months). Viewed separately, the follow-up for the PRECICE® group was 29.5months (16-48months) and for the Fitbone® group 29.4months (14 – 42months). (Tab.2)

## Table 1. Descriptive Statistical of Matched-Paired Patients

| Nail Type | Group A (PRECICE® nail) | | | | | | Group B (Fitbone® nail) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Items** | N | Range | Minimum | Maximum | Mean | SD. | N | Range | Minimum | Maximum | Mean | SD. |
| **Age of OP (yrs.)** | 19 | 28 | 15 | 43 | 25.7 | 8.9 | 19 | 24 | 16 | 40 | 25.0 | 8.2 |
| **Lengthening(mm)** | 19 | 40 | 20 | 60 | 34.3 | 10.2 | 19 | 32 | 23 | 55 | 34.1 | 8.2 |
| **OP to D-Stop(days)** | 19 | 109 | 23 | 132 | 47.1 | 24.9 | 19 | 80 | 35 | 115 | 55.7 | 23.0 |
| **OP-Full-Weight Bearing(days)** | 19 | 168 | 55 | 223 | 126.1 | 49.7 | 19 | 137 | 97 | 234 | 157.7 | 40.9 |
| **OP-Radiologic Consolidation(days)** | 19 | 254 | 86 | 340 | 160.4 | 75.1 | 10 | 128 | 152 | 280 | 217.0 | 42.6 |

Yrs.: Years, OP: Operation, D-Stop: Distraction stop, SD: Standard Deviation

## Table 2. Clinical Data of Matched-pair Patients (PRECICE® Nail, Fitbone® Nail)

| **PRECICE®** | Osteotomy | Leg | Entry Point | Age* | Length | DI | WBI | CI | Diagnose | **Fitbone®** | Osteotomy | Leg | Entry Point | Age* | Length | DI | WBI | CI | Diagnose |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **P.1** | femur p. | R | Ante | 15 | 25 | 0.89 | 34.4 | 3.44 | Congenital | **F.1** | femur p. | R | Ante | 18 | 28 | 0.67 | 54.3 | 5.43 | Congenital |
| **P.2** | femur p. | L | Ante | 29 | 30 | 0.66 | 28.4 | 3.29 | Congenital | **F.2** | femur p. | L | Ante | 30 | 28 | 0.47 | 42.1 | Null | Posttraumatic |
| **P.3** | femur p. | R | Ante | 19 | 22 | 0.82 | 40 | 4 | Posttraumatic | **F.3** | femur p. | R | Ante | 21 | 23 | 0.66 | 42.2 | 9.43 | Congenital |
| **P.4** | femur d. | R | Retro | 29 | 35 | 0.88 | 62.9 | 9,71 | Posttraumatic | **F.4** | femur d. | R | Retro | 25 | 38 | 0.54 | 34.2 | Null | Posttraumatic |
| **P.5** | femur d. | R | Retro | 30 | 25 | 0.46 | 43.6 | 7.44 | Posttraumatic | **F.5** | femur d. | R | Retro | 24 | 30 | 0.29 | 54.7 | Null | Posttraumatic |
| **P.6** | femur d. | L | Retro | 34 | 20 | 0.87 | 27.5 | 5.15 | Posttraumatic | **F.6** | femur d. | R | Retro | 40 | 25 | 0.68 | 45.6 | Null | Posttraumatic |
| **P.7** | femur d. | L | Retro | 35 | 30 | 0.97 | 30.7 | 3.1 | Posttraumatic | **F.7** | femur d. | L | Retro | 34 | 30 | 0.4 | 37.7 | Null | Congenital |
| **P.8** | femur d. | R | Retro | 19 | 40 | 0.8 | 20.8 | 4.1 | Congenital | **F.8** | femur d. | R | Retro | 17 | 38 | 0.66 | 47.9 | Null | Congenital |
| **P.9** | femur d. | R | Retro | 43 | 40 | 0.91 | 25.5 | 2,73 | Posttraumatic | **F.9** | femur d. | R | Retro | 36 | 38 | 0.61 | 43.2 | 5.39 | Posttraumatic |
| **P.10** | femur d. | R | Retro | 37 | 45 | 0.87 | 37.8 | 3.78 | Acquired | **F.10** | femur d. | L | Retro | 36 | 40 | 0.82 | 45.5 | Null | Congenital |
| **P.11** | tibia p. | L | Ante | 16 | 32 | 0.89 | 28.1 | 3.47 | Posttraumatic | **F.11** | tibia p. | R | Ante | 16 | 30 | 0.85 | 38.3 | 8.23 | Congenital |
| **P.12** | tibia p. | R | Ante | 37 | 35 | 0.58 | 58.9 | 9.3 | Congenital | **F.12** | tibia p. | L | Ante | 35 | 33 | 0.89 | 56.0 | 8.48 | Congenital |
| **P.13** | tibia p. | L | Ante | 34 | 27 | 0.9 | 42.6 | 4.26 | Posttraumatic | **F.13** | tibia p. | R | Ante | 28 | 31 | 0.62 | 42,9 | 5.16 | Posttraumatic |
| **P.14** | tibia p. | L | Ante | 18 | 32 | 0.94 | 37.5 | 4.03 | Acquired | **F.14** | tibia p. | R | Ante | 18 | 32 | 0.82 | 61.6 | 6.16 | congenital |
| **P.15** | tibia p. | R | Ante | 23 | 30 | 0.88 | 45 | 7.17 | Congenital | **F.15** | tibia p. | L | Ante | 27 | 27 | 0.68 | 80.7 | 8.07 | Acquired |
| **P.16** | tibia p. | L | Ante | 19 | 40 | 0.30 | 55.8 | 5.58 | Congenital | **F.16** | tibia p. | L | Ante | 16 | 40 | 0.90 | 47.7 | Null | Congenital |
| **P.17** | tibia p. | L | Ante | 18 | 53 | 0.87 | 18.3 | 2.33 | Congenital | **F.17** | tibia p. | R | Ante | 16 | 50 | 0.43 | 46.8 | 5.52 | Congenital |
| **P.18** | tibia p. | R | Ante | 18 | 60 | 0.78 | 27.2 | 3.5 | Congenital | **F.18** | tibia p. | L | Ante | 22 | 55 | 0.78 | 20.4 | Null | Congenital |
| **P.19** | tibia p. | L | Ante | 16 | 30 | 0.86 | 51,3 | 5.13 | Posttraumatic | **F.19** | tibia p. | L | Ante | 16 | 32 | 0.86 | 61.3 | 6.8 | Congenital |

P: Proximal, D: Distal, R: Right, L: Left DI: Distraction Index, WBI: Weight Bearing Index, CI: Consolidation Index.
*The age of the patients means the operative age.

## 6.1 Distraction, Weight Bearing and Consolidation Indices

All 38 patients had completed the lengthening process. The mean value of DI in Group A was 0.8mm/d (range: 0.3-1 mm/d), and the mean value of Distraction Index in Group B was 0.7mm/d (range:0.2-0.9 mm/d); the mean value of WBI between Group A and Group B differs from 37.7 d/cm (Range: 18.3-62.9d/cm) to 47.5 d/cm (Range: 20.4-80.7 d/cm); the average value of CI in Group A is 4.8 d/mm (Range: 2.3-9.7 d/mm), as to Group B is 6.9d/mm (Range: 5.2-9.4 d/mm). (Tab.3)

**Table 3. Descriptive Statistics of Matched-Paired Patients in Healing Indexes**

| Nail Type | Group A (PRECICE® nail) | | | | | | Group B (Fitbone® nail) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Items** | N | Range | Minimum | Maximum | Mean | SD. | N | Range | Minimum | Maximum | Mean | SD. |
| **DI (mm/d)** | 19 | 0.7 | 0.3 | 1 | 0.8 | 0.17 | 19 | 0.6 | 0.2 | 0.9 | 0.7 | 0.18 |
| **WBI(d/cm)** | 19 | 44.6 | 18.3 | 62.9 | 37.7 | 12.9 | 19 | 60.4 | 20.4 | 80.7 | 47.5 | 12.6 |
| **CI(d/mm)** | 19 | 7.4 | 2.3 | 9.7 | 4.8 | 2.13 | 10 | 4.3 | 5.2 | 9.4 | 6.9 | 1.56 |

DI: distraction index, WBI: weight bearing index, CI: consolidation index.

The results of the paired t-test showed that the DI value of Group A was higher than that of Group B, t = 2.214, $p = 0.04 < 0.05$, the difference was statistically significant. The WBI of Group A was lower than that of Group B, t = -2.82, $p = 0.0 < 0.05$, the difference was statistically significant. The CI value of Group A was lower than that of Group B, t = -3.888, $p = 0.004 < 0.05$, the difference was statistically significant. By subgrouping the osteotomy sites into proximal femur, distal femur and proximal tibia, we found there were no statistically significant differences among three osteotomy site groups: DI ($p = 0.430>0.05$), WBI ($p = 0.446>0.05$), CI ($p = 0.517>0.05$).

In order to get more information from the paired patients, we categorized the patients according to diagnosis (congenital, acquired and posttraumatic) after we have paired the patients. Even in the first hand, we did not accept etiology as in the inclusion criteria , but with other equivalent factors, using etiology as the variable and analysis each three etiological groups among PRECICE® nail patients and Fitbone® nail patients, non-parametric test showed that there was no significant difference in DI ($p = 0.153 > 0.05$), WBI ($p = 0.846 > 0.05$) and CI ($p = 0.911 > 0.05$) among the three groups when nail type = PRECICE®, non-parametric test also showed that there was no significant difference in DI ($p = 0.334 > 0.05$), WBI ($p = 0.091 > 0.05$) and CI ($p = 0.111 > 0.05$) among the three groups when nail type = Fitbone®.

## 6.2 Complications of Both Groups

According to Lee's intramedullary lengthening classification system,[54] there are three types of general complications, including problems, obstacles, and sequela.

Type-1 is distraction control-related complications, such as runaway, nonfunctional nails and so on; Type-2 is mechanical strength of the nail (stability), such as breakage of the nail and crown breakage; Type-3 complication is non-implant-related complications that does not affect the primary function of the nail, such as corrosion, adverse reaction of the tissue, heterotopic ossification, delayed union and so on, each type includes three subsections (problem, obstacles and sequelae).

There were eight problems, three obstacles and no sequelae happened in patients lengthening by PRECICE® nails (Group A) in total; and nine problems, four obstacles and no sequelae happened in patients lengthening by Fitbone® nails (Group B) in total.

In Group A patients, there were eight Type-3 problems (pain during lengthening ×1, subjective prolongated ×1, equinus contracture ×3, soft-tissue irritation around screws ×1, medication side effect ×1 and false setting of the ERC×1), three Type-3 obstacles (insufficient bone regeneration ×1, screw dislocations ×2), and one Type-2 obstacle (crown breakage ×1). (Fig.13)

In Group B patients, there were two Type-1 problems (backtracking ×2), seven Type-3 problems (irritation around subcutaneous receiver ×2, equinus contracture ×2, irritation around screws ×2, knee contracture ×1), and four Type-3 obstacles (superficial peroneal nerve compression ×2, slow bone regeneration ×1, sensibility disorder around subcutaneous receiver ×1). (Fig.14)

Both of the groups' patients had no sequelae found in this study.

## 6.3 Complications of Group A

### 6.3.1 Problems of Group A

1. Patient-P2: The first 2weeks after discharge from hospital, the patient had pain and 14day only lengthen for 10mm, and we gave the patient Tramadol (50-0-100mg), slow down the lengthening according to the patient's tolerance of pain until the next visit, the

patient said the pain during lengthening became much better and stopped the medicine, then continued lengthening as planned.

2. Patient-P7: The patient subjectively felt too long after the preplanned procedure of the lengthening, then shortened for 5mm in 5days after distraction stop.
3. Patient-P7: During the lengthening, the patient felt slightly irritated around one interlocking screw, regular follow up and no special treatment was given.
4. Patient-P12: The patient had peri malleolar swelling pressure pain over malleolar medial causing equinus contracture, the patient stopped lengthening for 3 days because of the pain, then he received electrotherapy, the pain in Achilles tendon is decreasing and gradually lengthen the patient coupled with intensive physiotherapy.
5. Patient-P16: The patient got very resistant equinus contracture, we did shorten the patient for continuous 7 days for 7mm, then slowed down the speed of lengthening from 1mm per day to 0.5mm per day along with intensive physiotherapy.
6. Patient-P17: During the early stage of the lengthening, we found the patients did not regularly lengthen (4mm for 7days), it is because of the false setting of the magnet marker, with one more meticulous instruction with the patient, corrected immediately.
7. Patient-P17: Equinus contracture was found during lengthening, we slowed down the lengthening speed and increased the physiotherapy intensity.
8. Patient-P18: The patient complained urticaria in the region of the thigh and popliteal fossa, we thought antipyretic analgesics' side effect may be the reason, so we changed from metamizol to paracetamol.

### 6.3.2 Obstacles of Group A

1. Patient-P5: The patient had a traffic accident which caused a complex, multi-dimensional malalignment and relevant shortening. During consolidation period, we had noticed that the patient showed insufficient bone regeneration, 6 months after distraction stopped, we did a debridement to boost bone regeneration and exchanged the lengthening nails with a solid nail in case of length loss, which showed regular remodelling afterwards.
2. Patient-P5: The crown breakage of this patient (Fig.15) was found during the surgery of removing PRECICE® nail. At this point, the patient had achieved the length, so no special treatment concerning crown breakage was given, but document this obstacle. (see more in the discussion)

3. Patient-P13: This patient had one proximal screw dislocated, a revision surgery was done to stabilize the screw and no further complication occurred.
4. Patient-P18: This patient had one distal trans fixation screw (3.5mm) broken, a revision surgery was done to replace the screw.

### 6.3.3 Sequelae of Group A

There were no sequelae in the group A patients.

## 6.4 Complications of Group B

### 6.4.1 Problems of Group B

1. Patient-F1: The patient's document showed that he had backtracking twice (3mm and 1mm) after reaching the final length, and we re-lengthened the patient for compensation and monitored this problem until partial consolidation in case of backtracking again.
2. Patient-F2: The patients had mild irritation around the subcutaneous receiver, and we slowed down the speed of lengthening.
3. Patient-F4: Equinus contracture was found during lengthening. We instructed the patient to slow down the lengthening speed and increase the physiotherapy intensity.
4. Patient-F7: The patients had slight irritation around the proximal screw head, we prescribed with regular follow up and no special treatment was given.
5. Patient-F7: During the lengthening, the patient's complaint about the knee flexion contractures, we prescribed the patient a redressing cast to assist the knee movement for 1 weeks, also increased intensity of physiotherapy.
6. Patient-F8: Equinus contracture was found during lengthening. Slowing down the lengthening speed and increasing the physiotherapy intensity.
7. Patient-F10: The patients had mild irritation around the proximal screw head, regular follow up and no special treatment was given.
8. Patient-F13: The patients had mild irritation around the subcutaneous receiver, and we slowed down the speed of the lengthening with standard follow up.
9. Patient-F17: After distraction stopped, we noticed the patient backtracked 3mm in 2 weeks, but no further re-lengthening was prescribed for this patient.

### 6.4.2 Obstacles of Group B

1. Patient-F10: We noticed this patient had slow bony regeneration, in order to accelerate the regeneration of the callus and reaching full weight bearing more quickly, bone grafting harvested from equilateral iliac crest was operated for accelerating bone regeneration and later with uneventful remodeling.
2. Patient-F11: Patient described paraesthesia and pain around the knee after surgery, neurologist was consulted and suggested to remove the additional blocking screw, the patient's sense recovered progressively, but with no final follow-ups documented.
3. Patientin-F12: After implanting the nail, because of the hematoma around subcutaneous receiver, which made the transmission between electric transmitter and subcutaneous receiver difficult, so we did a revision surgery was cleaning the hematoma.
4. Patient-F19: The patient had sensibility disorder around 6 x 6cm lateral to the subcutaneous receiver after reaching the final length, neurologic expertise recommended to remove the subcutaneous receiver, we did a revision surgery to resolve this obstacle.

### 6.4.3 Sequelae of Group B

There were no sequelae in the Group B patients.

# 7. Discussions

## 7.1 Rationale for Matching Criteria

Limb length discrepancy (LLD) is a relatively common diagnosis that can be found by up to 90% of the population.[68] LLD is also responsible for standing balance, low back pain, stress fracture, osteoarthritis, and associated running injuries.[69] Distraction osteogenesis by external fixation is a well-known international treatment of treating orthopedic extremity deformity, but with considerable complications, which has been explained above. In order to obviate such a situation, several fully implantable lengthening nails had been produced.[25,31,32,34,38,64] But until

68. Guer JL, 2017 „ Does Intensive Soccer playing during the Growth Period Lead to Leg Length Discrepancies? ".

69. Gurney B, 2002 „ Leg length discrepancy ".

now, only case series on individual treatment to evaluate treatment and complications of intramedullary nail systems. Even though several matched-paired literatures of lengthening over nail comparing with traditional external lengthening system (Ilizarov) and on lengthening nails versus traditional external lengthening system (Ilizarov) has been studies, but it was not between two intramedullary nails, and they all used Paley's external lengthening classification system which is not particular suitable for intramedullary nails. The aim of this study is to directly compare the advantage of the complications and effectiveness of two currently dominant nails, the matching criteria were selected in such a way that, in our experience, the relevant parameters for the outcome of distraction treatment are as similar as possible. This is the first match pair analysis comparing two dominant intramedullary lengthening systems (PRECICE® and Fitbone® nail) adopting with intramedullary lengthening classification system.

### 7.1.1 Distraction

The planned distraction goal directly contributes to the duration of the treatment.[70] With long-length distractions, the stress on the connective tissue increases and with it the frequency of complications such as equinus contracture, delayed or early maturation of regenerated bone, which also impaired with increasing distraction length. For this reason, the distraction distance was considered to be decisive for the difficulty of the treatment and the allowed deviation of +/- 20% was chosen relatively acceptable. The decision to use a relative value (%) and not an absolute value (mm) was made in order to meet the relatively higher demands of large distraction length better. For example, this means that for a Fitbone® patient with a planned distraction distance of 40 mm, the comparable Fitbone® patient should have a planned distraction distance between 32 mm and 48 mm.

### 7.1.2 Patients' Age

When it comes to the age of the patients, a deviation of 20% was allowed in this paired study. Young patients were not operated on until the bone growth had been completed radiologically. A comparison of the bone ingrowth with an adult bone is therefore excluded in advance, the study of Noonan also showed the significant difference in healing index existed between the patients over 14 and below 14, all the patients included in this study was above 14.[71] However,

70. Watanabe K, 2013 „ Over 10-year follow-up of functional outcome in patients with bone tumors reconstructed using distraction osteogenesis ".

71. Noonan KJ, 1998 „ Distraction osteogenesis of the lower extremity with use of monolateral external fixations. A study of two hundred and sixty-one femora and tibiae ".

since adult bone continuously loses its degree of mineralization over the course of its lifetime and signs of aging are also to be expected for new bone formation, the treatment of distraction in older patients simply from the biology of the bone is more complicated.[72] There was a study [73] showed that from 319 cases with distraction treatments, in four age groups, the youngest was under 10 and the oldest was over 22; the wearing time of the fixator increased significantly with age. Regardless of this, the general morbidity that increases with age must be taken into account. For this reason, the age at the time of implantation was included in the matching with a possible deviation of +/- 20%. For example, Fitbone® patient 20 years old at the time of the operation would therefore need a PRECICE® patient as a matching partner who is between 16 and 24 years old at the time of the operation. The basis for choosing a relative value (%) for this decision is again the large number of different age groups of the patients in case of better argumentation and comparability.

### 7.1.3 Surgical Techniques

Studies have shown that depending on the degree of difficulty, distraction osteogenesis requires 20-40 operations before a physician's complication rate drops significantly.[74] But this study included only patients treated with external fixator, considering the implantation of an intramedullary lengthening nail is more complex and the learning curve is much steeper,[36,37] because unlike the external fixator, does not allow any changes afterward, especially the meticulous follow-up, the treatment concerning the mechanics, distraction-related complications, and the management of specific lengthening nail patients.

This study was based on 241 Fitbone® nail patients and 62 PRECICE® nail patients, who were all operated and followed up by the same surgeon. The identical surgical techniques of the same surgeon and a large number of cases in the comparison group enable valid matching pairs. When matching the pairs, the patients treated with PRECICE® nail were preferred, so that the operations with the higher expertise were always selected.

72. Chan GK, 2002 „Age-Related Bone Loss ".

73. Koczewski P, 2013 „Factors Influencing Bone Regenerate Healing in Distraction Osteogenesis ".

74. Dahl MT, 1994 „Complications of limb lengthening. A learning curve ".

### 7.1.4 Osteotomy Site

There are two osteotomies (distal and proximal osteotomy) on the femur. The location of the osteotomy and the route of implantation are interdependent. When the osteotomy is at the proximal of the diaphysis, the intramedullary nail is inserted antegrade. With a distal osteotomy, the intramedullary nail is usually inserted retrograde starting from the knee joint. An exception is the rarely used Fitbone® SAA nail, which is also inserted antegrade with a distal osteotomy, and had been explained in chapter 2.4 and 4.5.1. With regard to the biological characters of the bones to be lengthened and their reaction to damage, there are differences depending on the location: the blood flow to the bone continuously decreases from proximal to distal, an osteotomy in the metaphysis shows better healing than a diaphysis osteotomy and the consolidation times for tibia and femoral osteotomies often differ. Therefore, only cases with the same osteotomy location were compared.[75,76]

### 7.1.5 Mechanical Axis Realignment

With a distal osteotomy on the femur and osteotomy on the tibia, it is possible to carry out a significant correction of existing malalignments of the leg axis in the course of distraction treatment. This requires increased demands on the planning and execution of the operation. Only cases in which a realignment of any kind was made were included in the study. No matching criteria were made with regard to the degree of correction. In the case of varus or valgus malposition, the level of the correction also correlates with the contact area of the bone ends in the area of the osteotomy, so an effect on bone healing could be assumed. We have found a study[72] of 319 cases with distraction osteogenesis using the Ilizarov method that the mechanical axis realignment did not influence the wearing time of the fixator Further publications on this topic, especially with regard to fully implantable nails, are currently still missing.

### 7.1.6 Nicotine Withdrawal during Treatment

Nicotine consumption has been shown to be harmful. With regard to bone metabolism, it is known that nicotine leads to mineralization disorders and increases the risk of delayed bone

75. Kunze K., 1981 „Veränderungen der Knochendurchblutung nach Osteotomien und Osteosynthesen “.

76. Fischgrund J., 1994 „Variables affecting time to bone healing during limb lengthening “.

healing up to the formation of pseud arthrosis.[77] It is, therefore advisable not to consume any nicotine in the case of bone injuries; this applies in particular to lengthening treatments using intramedullary nails. [78] For this reason, nicotine withdrawal is a prerequisite for low-complication distraction treatments. Despite extensive preoperative clarification of this connection, some patients still continued to experience nicotine abuse amount during treatment. These cases were excluded from the study to avoid controversy results.

### 7.1.7 Classifications of Complications

Currently there are two primary lengthening systems: External and Internal lengthening systems, and both of the systems have its own complication classification systems; one is for external fixator, several publications had been released so far.[52,79,80,81,82] of which Paley's classification system was frequently used in the literature. With the development of new lengthening systems, classifying the complications using only external fixator method is not sufficient anymore, because complications of lengthening has its own additional characters besides the common complications(local or systemic and intraoperative, early or late stage of recovery) of any operation, such as the different lengthening mechanics and during distraction stage. Considering the different lengthening mechanics, any incidents that happen during distraction stage related to the nails and better understanding of the merits and demerits of intramedullary lengthening systems, Lee had published the new classification systems specially designed for intramedullary nails in 2017.

In Lee's classification system, his prime types of complications are as followed: Type-1 is distraction control-related complications, such as runaway, nonfunctional nails and so on; Type-2 is mechanical strength of the nail (stability), such as breakage of the nail; Type-3 complication is non-implant-related complications that does not affect the primary function of the nail. The reason why he classified as above is because with years of amassing experience, the

77. Lee JJ. 2013 „The Musculoskeletal Effects of Cigarette Smoking ".

78. Zheng LW, 2008 „Changes in Blood Perfusion and Bone Healing Induced by Nicotine during Distraction Osteogenesis ".

79. Caton J., 1985 „ Intermediate results of a series of 33 cases of leg lengthening using H. Wagner's technic ".

80. Popkov AV., 1991„ Errors and complications of operative lengthening of the lower extremities in adults by the Ilizarov method ".

81. Donnan LT, 2003 „ Acute correction of lower limb deformity and simultaneous lengthening with a monolateral fixator ".

82. Lascombes P., 2012 „ Classification of complications after progressive long bone lengthening: Proposal for a new classification ".

complications such as imprecise lengthening rate, mechanical failure and broken external controller are either overlooked or classified in the non-optional sections and nonsurgical techniques, the complications related to the fully implantable nails itself are supposed to be one of the primary complications for intramedullary systems. In the new classification system, specific external fixator complications were deleted such as pin-tract problems.

Comparing with Paley's external fixation's complication classification system, it is more suitable to categories the complications of intramedullary nail system implementing customized classification system.

## 7.2 Discussion of the Results

The purpose of evaluating the outcome implementing the distraction index (DI), weight bearing index (WBI), consolidation index (CI) was to enable a high level of comparability with other studies. Even though the selection of the most frequently used units for all three parameters differs in different studies, for example, some of the studies used mm/d in DI [64,83] ,and other studies used d/mm as the unit in describing DI.[84,85] But this kind of difference in comparability is limited to a very small extent.

Comparing with Paley's classification, [53] the classification of complications that we used in this study was from Lee's[54] newly established category specially designed for fully implantable nails, which should be more suitable for the intramedullary nails. As the first matched pair analysis comparing two dominant intramedullary lengthening systems (PRECICE® and Fitbone®) applying the new intramedullary lengthening classification system. Our results showed that two nails (PRECICE® and Fitbone®) had different kinds of complications, PRECICE® nail patients in this study showed Type2 and Type-3 complications, which is mechanical strength of the nail and non-implant-related complications that do not affect the primary function of the nail, however, Fitbone® nail patients had Type-1 (distraction control-related complications) and Type-3 complications.

83. Kenawey MC. 2010 „ Insufficient Bone Regenerate after Intramedullary Femoral Lengthening: Risk Factors and Classification System ".

84. Dinçyürek HM. 2012 „Functional results of lower extremity lengthening by motorized intramedullary nails ".

85. Krieg AH. 2008 „Leg lengthening with a motorized nail in adolescents: an alternative to external fixators? ".

The complications frequently reported on PRECICE® nail is the breakage of the nail, crown breakage and screw dislocation,[38,65] breakage of the nail is mainly because of its own unique mechanical design of the nail: The thinner-thread rod and the internal nail part moves freely from the nail sleeve, both can unintentionally happen when PRECICE® nail works against premature consolidation or exceeding the minimal beginning position when shortening. The design of the thin magnetic metal spindle and the comparatively fragile parts (crown and fins), which represents the anti-rotation mechanism of the nail, may also indirectly contribute to the comparatively easier dislocation of the screw. In our study, P5 patient had insufficient bone regeneration, six months after distraction stopped, we did a debridement to boost bone regeneration and exchanged the lengthening nails with a solid intramedullary nail in case of length loss; the breakage of the crown was also found after removing PRECICE® nail (P2) in the surgery. In this patient's situation, it was difficult to distinguish exactly when the crown broke. The breakage of the crown could be the reason of insufficient bone regeneration, because the anti-rotation mechanism part (crown and fins) had been broken (Fig.16) and instability of the nail made the regeneration difficult, maybe because the nail handled too early weight bearing or just because the crown and pins are the fragile part of the PRECICE® nail. In this case, we still decided to classify this into the Type-2 obstacle of the complication. Because no matter what was the reason that caused the crown breakage, it was all related to the mechanical strength of the nail.

Patients' false application of the ERC can also happen commonly in PRECICE® patients, false setting of the ERC will make the magnetically induced rotation insufficient or difficult, which will result in unplanned lengthening or inadequate lengthening which leads to early bone formation. All these complications can be avoided or at least noticed by meticulous treatment pre-planning, careful instruction on how to use the ERC, and the most important is for the patients to spend the entire period of lengthening close enough to have a comprehensive follow-up of the whole process. During the lengthening, P17 patient's irregularly lengthening was noticed, after talking with the patient, we found out that the patient did not arrange the ERC as instructed and also mark the wrong magnet on the lower limb, another meticulous instruction was made for the patient to avoid this happen again. In this study, we did not find any nail breakage, but two screw related complication (P13 and P18 patients) were found. P13 patient had one proximal screw dislocated, a revision surgery was done to stabilize the screw and no further complication occurred, P18 patient had one distal trans fixation screw (3.5mm) broken, a revision surgery was done to replace the screw. Another problem that happened in PRECICE®

nail patient was three cases of equinus contractures and one case of knee flexion contraction, temporarily slowing down the speed of lengthening, increase the intensity of physiotherapy and with auxiliary tools such as quengel casting seem to be proper treatment. Except for patient P12, who also got have also got equinus contractures caused by peri malleolar swelling and pressure pain over malleolar medial, extra electrotherapy was prescribed for this patient. P16 patient had resistant equinus contractures, after intensive physiotherapy, there was no sign of improvement, we decided to shorten the nail for a week, then slow down the speed of lengthening from 1mm/d to 0.5mm/d still with intensive physiotherapy. In this study, we found one patient (P7) felt subjectively overlengthened and demanded 5mm shortening after distraction stopped, we had succeed in shortening the nail and achieved satisfied results, which showed the advantage of the PRECICE® nail (the ability of shortening and lengthening) that is also the only nail currently available that can do bi-directionally currently. P18 patient got urticaria in the region of the thigh and popliteal fossa, after changing metamizol to paracetamol, the syndrome went away. According to our experience, the patients who underwent intramedullary lengthening normally did not complain too much about the pain, In this study we found that patient P2 complaint about lengthening during the first two week after discharging from the hospital, which induced insufficient lengthening (14days only 10mm), so we prescribed Tramadol (50-0-100mg) and suggested the patient to slow down a little bit according to the tolerance of the pain until the next visit.

In this study, we did not find any PRECICE® patients that have distraction control-related complications, or direct nail breakage. But in 2013 we had our first experience dealing with PRECICE® nail breakage (Fig.17). It was with one young female patient inserted first generation of PRECICE® nail (P1). The breakage happened during consolidation period, we did successfully remove the broken nail, and replaced it with a solid intramedullary nail to reduce the risk of length loss. In order to alleviate such complications frequently reported by surgeons, the company promoted the second generation of the PRECICE® nail (P2) in 2012 with much more robust device. In December 2014, a modified mode of generation two PRECICE® nail (P2.1) was also available in the market.[86] But much large clinical trial needs to be done to verify our theories about PRECICE® nail.

86. Panagiotopoulou, V.C., 2018 „ A retrieval analysis of the PRECICE intramedullary limb lengthening system “.

But in Fitbone® nail patients, we have noticed F1 patient had backtracked twice (3mm and 1mm) after reaching the final length, and we re-lengthened the patient for compensation and monitored this problem until partial consolidation  in case of happening again, F17 patient backtracked 3mm in 2 weeks after distraction stopped, but no further re-lengthening was prescribed for this patient. Backtracking is often reported as a complication of Fitbone® nail.[37] F1 patient was lengthened again after the distraction loss to make up to the final lengthening goal, and special follow-up with several additional x-rays was given to control this situation. Back tracking seems to be caused by thousands of repetitive micro-movements at the telescoping part of the nail. These micro-actions are transmitted through the gearbox to the electric motor and cause shortening until the final consolidation. But from Accadbled's recent study[35] showed that no backtracking was found, maybe attributed to a minor technical improvement made by the manufacturer to prevent backtracking of the system, but still need larger clinical trials to confirm. Another obstacle that frequently happened in the Fitbone® patients is the complications around the subcutaneous receiver, For example, F12 patient: After implanting the nail, because of the hematoma around subcutaneous receiver, which made the transmission between electric transmitter and subcutaneous receiver difficult, so we did a revision surgery was cleaning the hematoma. F19 patient: After the whole lengthening treatment was done, the patient developed a sensibility disorder around 6x6cm lateral to the subcutaneous receiver, and an additional surgery was scheduled to remove the subcutaneous receiver, then the patient progressively regained the sensibility. Patients such as F13 had complained about a mild uncomfortable around subcutaneous receiver, but no special treatment was given to the patient when it happened.

In the Fitbone® patient, we also found F11 patient described paraesthesia and pain around the knee after surgery, neurologist was consulted and suggested that we should remove the additional blocking screw, after the surgery, the patient's sense recovered progressively, but unfortunately with no final follow-ups of this patient. F10 patient got slow regeneration of the callus during the lengthening, debridement and bone grafting harvested from the equilateral iliac crest was performed to treat the insufficient and slow regeneration, and later with uneventful remodeling. Other problems, such as equinus contractures and irritation around screws also happened in Fitbone® nail patients.

In both of the two group patients did not have accelerated lengthening[31,32,33] (DI more than 1.5mm/d), which coincided with current studies with both kinds of nails. Frequent backtracking

of Fitbone® nail patients resulted in a lower mean of DI 0.7mm/d (range:0.2-0.9 mm/d), and results of paired t-test also showed that the DI value of Group A was higher than that of Group B, t = 2.214, $p = 0.04 < 0.05$, the difference was statistically significant. In the very beginning of this study, we did not consider including consolidation index as the measure parameter, because, First, from its definition: CI was calculated from the interval of the operation date to the date of radiographic consolidation divided by the length of the distraction gap, and in order to define radiographic consolidation,[87] at least three of the four cortices from anterior-posterior and lateral radiographs should be consolidated. Furthermore, x-rays in the later consolidation phase are taken every 6 to 12 weeks only, which both means it can be very subjective to decide the specific point in time. Second, both WBI and CI are used as healing index, WBI is comparatively objective, because it needs to be conjunction with both X-ray images and patients' full weight bearing behavior. But in order to see if both of the healing indexes can be consistent, we finally came to the conclusion to document the radiographic consolidation date. In order to be more objective, the final radiographic consolidation date of each patient was under two physicians' agreement. Both WBI and CI of Group A was lower than these of Group B, and the differences were statistically significant, which clinically means that the average recovery time of the whole treatment from Group A is shorter than Group B in both WBI and CI in our study. The reason why Fitbone® nail patients' recovery time of the whole treatment (especially considering in healing indices) are longer than PRECICE nail® patients is mainly because the characters of the Fitbone® nail - backtracking. The patient needs to compensate for the lengthening loss almost every time when backtracking happens, which makes the lengthening procedure longer than original plan.

By subgrouping the osteotomy sites into proximal femur, distal femur and proximal tibia, we found there were no statistically significant differences among three osteotomy site groups: DI ($p$=0.430>0.05), WBI ($p$=0.446>0.05) and CI ($p$=0.517>0.05).This result may differ from some colleagues' impression, because in clinical experience, the osteotomies on the tibia and distal femur near the knee tend to have soft tissue problems in the form of movement disorders. Furthermore, the vascular supply of an extremity decreases from proximal to distal, poor blood supply and soft tissue cover may be the reason why the fractures of the tibia shaft tend to heal

87. Balemane S., 2016 „Prospective study of treatment of non-union of tibia using limb reconstruction system with intramedullary nailing ".

more slowly than femoral shaft.[88,89] But WBI and CI, as healing indices, should be good clinical measuring parameters instead of revealing the actual lower limb healing time. From their definition, WBI only needs one side of the four cortices was seen to be intact on the anteroposterior and lateral radiographs, and CI needs three of four cortices were seen to be intact on the anteroposterior and lateral radiographs. Both of them do not require the time of final unite of osteotomy to be calculated, which means these healing indices should be independent from the bony healing ability. But because of the limited number of each paired groups, a further large clinical study should be implemented to confirm this finding.

Since initially we did not define pathogenesis as a pairing inclusion criteria, after pairing the patient with the five criteria above, we did an analysis among the patients respectively within two kinds of nails, statistically finding out there was no significant different in DI, WBI and CI, which with limited evidence as the etiology of the LLD is less crucial comparing with the performance of the nails itself.

## 7.3 Limitations

Because of limited case load and the highly demanding inclusion criteria, only a small amount of matched pair patients was included in the final analysis. Both WBI and CI are usually described as a healing index, but comparing with WBI, CI, as a parameter, can be very subjective and depend much more on patient medical compliance comparing with WBI.

The Null CI data from Tab.2 could also reveal the importance of patient medical compliance. Because the patients did not show up in the clinic according to the schedule, or some of the radiographic follow-up data were missing since Fitbone® patients can be traced back to 2003. The radiologic consolidation x-rays after distraction stopped cannot be precisely documented. The reasons why we still included CI, even WBI can also be sufficient enough as the healing index, is because in this study we try to have a more comprehensive understanding of two nails performance.

There are several other considerations, such as the status of soft tissue, bone mineral density

88. Wraighte PJ. 2006 „ Principles of fracture healing".

89. Roermund PMV. 1988, „ Bone Healing During Lower Limb Lengthening by Distraction Epiphysiolysis ".

and so on, which might influence the result of limb lengthening. However, after discussion, we still embraced the five matching criteria to prevent even a smaller number of matching pairs, and we estimate that with more matching criteria or tighter ranges for the specific criteria the number needed to treat would grow higher than any institution can provide. But it is also just because of these limitations that they reflect the true course of standardized clinical treatment by surgeon and supervision of one surgeon on each patient.

# 8. Conclusions

Different techniques can be used to compensate for leg length discrepancy (LLD) using distraction osteogenesis. External fixators, the lengthening over nail (LON) technique, and fully implantable nails are all currently in clinical practice. The comfort for the patient is much higher with the purely intramedullary systems than with external fixators or LON. At the meantime, the implantation and postoperative handling places high demands on the attending physician and the patient. By time only one or two implants are freely available. The individual properties of the different systems must be taken into account.

When choosing the implant, the individual properties of the different systems must be taken into account. New intramedullary lengthening nails, such as the third generation of PRECICE® STRYDE nail, which is claimed to allow patients to have immediate fully weight bearing after operation, are still at the beginning of their clinical application and to our knowledge so far, we did not find any publications.

Due to a comparing small incidence of limb lengthening surgeries, there is a lack of compelling studies on intramedullary lengthening systems. Direct comparison of specific devices with equivalent treatment protocols and even much higher cases will serve further important information on the efficiency and complications of the lengthening systems.

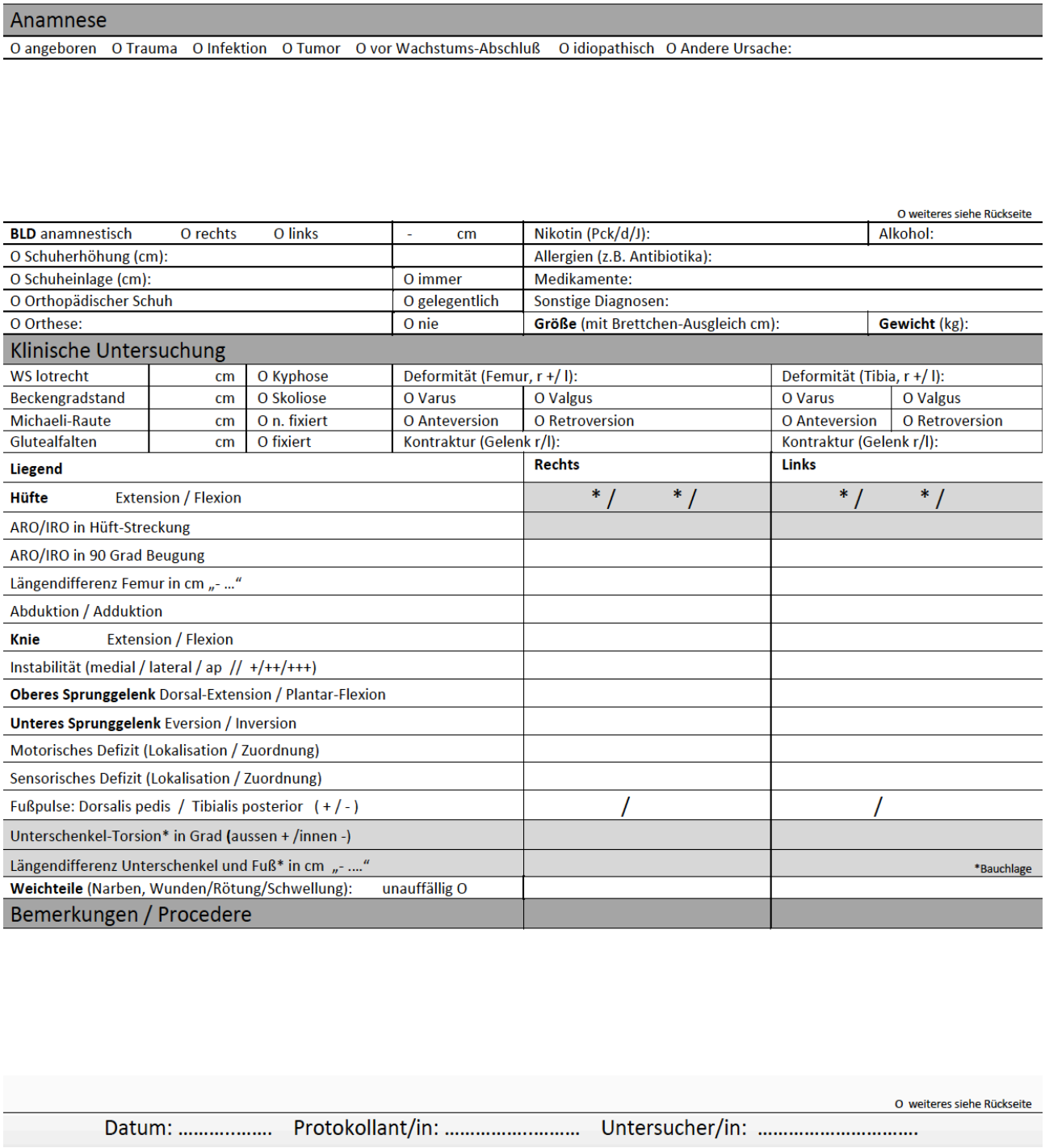
Both of these two nails (Fitbone®, PRECICE®) from this study lead to satisfactory results, which means either PRECICE® nail or Fitbone® nail is a good clinical candidate for treating LLD. Even the complications concerning its own mechanism could be monitored or highly avoided by a meticulous, standardized clinical treatment plan, and the manufactures keep improving their products' performance. Because of the versatile performance of the PRECICE® (shorten and lengthen), it is easier to adjust accordingly, but still the fragile of the PRECICE® nail(thinner-thread rod) and the function of the ERC could be a problem for the obesities and

these patients who handle too early weight bearing, even though the company had launched a third generation(PRECICE® STRYDE) in the late 2018, which is announced as immediate full weight bearing after operation, but the spread of clinical usage still needs some time. However, unlike the external fixation or PRECICE® nail, no adjustment can be made postoperatively for Fitbone® nail, so highly rigorous and meticulous preoperative planning and postoperative lengthening process is much more demanding than PRECICE® nail. Etiology and osteotomy site did not influence as much as the nail differences according to the results of this study.

At the current state of technical development, scientific and clinical knowledge, we recommend close follow-up of distraction and consolidation phase in all procedures in order to facilitate the early detection of general problems in limb lengthening and especially specific problems concerning different mechanisms of the nails.

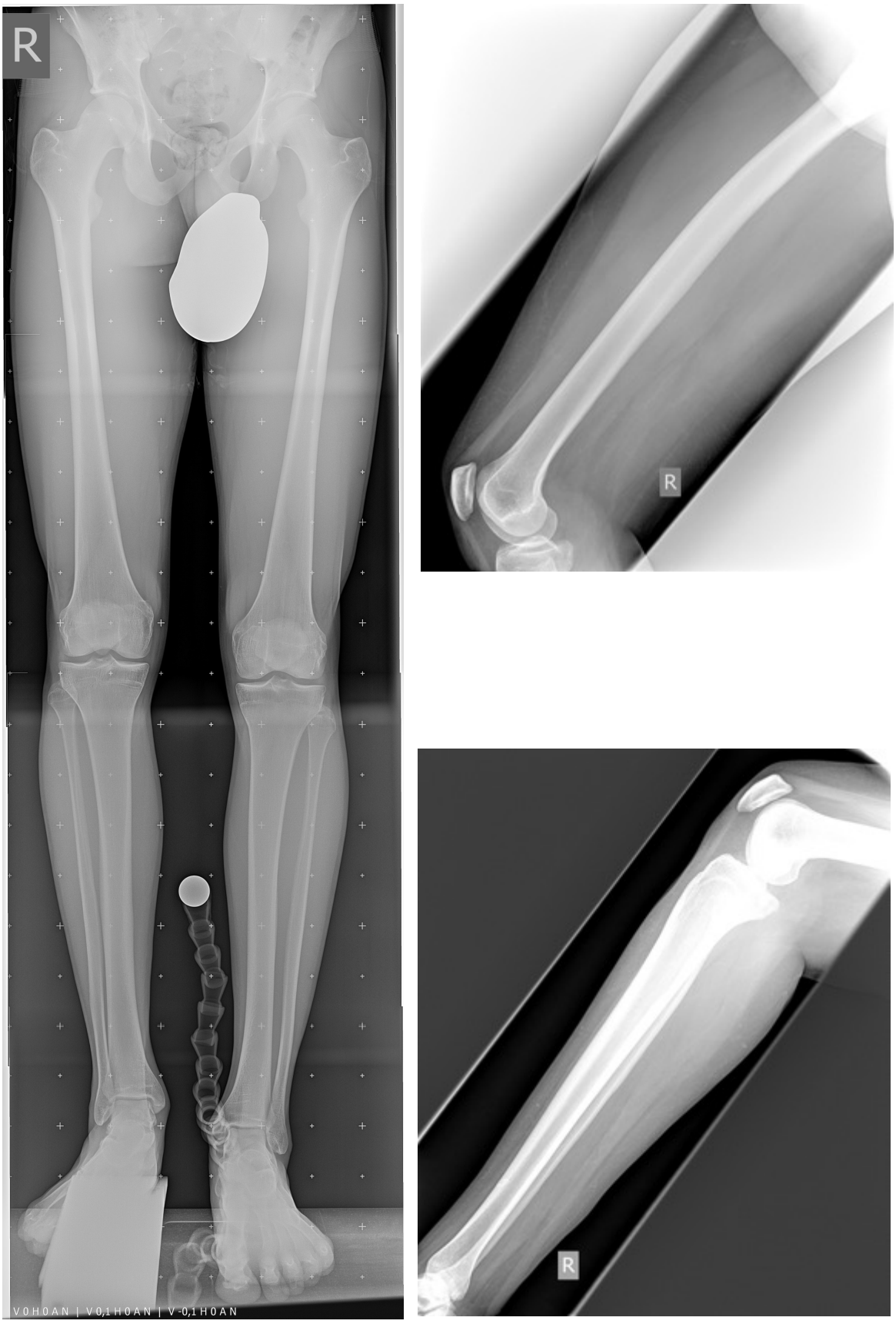
# 9. Supplementary Data

## 9.1 Figures

- 

| Anamnese | | | | | | |
|---|---|---|---|---|---|---|
| O angeboren O Trauma O Infektion O Tumor O vor Wachstums-Abschluß O idiopathisch O Andere Ursache: | | | | | | |
| | | | | | | O weiteres siehe Rückseite |
| **BLD** anamnestisch O rechts O links | | | - cm | Nikotin (Pck/d/J): | | Alkohol: |
| O Schuherhöhung (cm): | | | | Allergien (z.B. Antibiotika): | | |
| O Schuheinlage (cm): | | | O immer | Medikamente: | | |
| O Orthopädischer Schuh | | | O gelegentlich | Sonstige Diagnosen: | | |
| O Orthese: | | | O nie | **Größe** (mit Brettchen-Ausgleich cm): | | **Gewicht** (kg): |
| Klinische Untersuchung | | | | | | |
| WS lotrecht | cm | O Kyphose | Deformität (Femur, r +/ l): | | Deformität (Tibia, r +/ l): | |
| Beckengradstand | cm | O Skoliose | O Varus | O Valgus | O Varus | O Valgus |
| Michaeli-Raute | cm | O n. fixiert | O Anteversion | O Retroversion | O Anteversion | O Retroversion |
| Glutealfalten | cm | O fixiert | Kontraktur (Gelenk r/l): | | Kontraktur (Gelenk r/l): | |
| **Liegend** | | | | **Rechts** | **Links** | |
| **Hüfte** Extension / Flexion | | | | * / * / | * / * / | |
| ARO/IRO in Hüft-Streckung | | | | | | |
| ARO/IRO in 90 Grad Beugung | | | | | | |
| Längendifferenz Femur in cm „- ...“ | | | | | | |
| Abduktion / Adduktion | | | | | | |
| **Knie** Extension / Flexion | | | | | | |
| Instabilität (medial / lateral / ap // +/++/+++) | | | | | | |
| **Oberes Sprunggelenk** Dorsal-Extension / Plantar-Flexion | | | | | | |
| **Unteres Sprunggelenk** Eversion / Inversion | | | | | | |
| Motorisches Defizit (Lokalisation / Zuordnung) | | | | | | |
| Sensorisches Defizit (Lokalisation / Zuordnung) | | | | | | |
| Fußpulse: Dorsalis pedis / Tibialis posterior ( + / - ) | | | | / | / | |
| Unterschenkel-Torsion* in Grad (aussen + /innen -) | | | | | | |
| Längendifferenz Unterschenkel und Fuß* in cm „- ....“ | | | | | | *Bauchlage |
| **Weichteile** (Narben, Wunden/Rötung/Schwellung): unauffällig O | | | | | | |
| Bemerkungen / Procedere | | | | | | |
| | | | | | | O weiteres siehe Rückseite |
| Datum: ..... Protokollant/in: ..... Untersucher/in: ..... | | | | | | |

- **Fig.1: Documentary file of clinical physical examination used in outpatient department**




- **Fig.2: Standard radiologic assessments include diagnostic lateral view for targeted lower limbs, and long standing radiograph x-rays**

- Untersucher:

  Datum:

Analyse der LAIS

| LAIS mit ..... mm ▫ rechts ▫ links | rechtes Bein | linkes Bein |
|---|---|---|
| Oberschenkel [mm] | 545 | 564 |
| Unterschenkel [mm] | 421 | 429 |
| Gesamtlänge [mm] | 972 | 999 |
| Mech. Achsdeviation in Höhe KG (mm, M=med, L=lat) | 18M | 8M |
| Caput-Collum-Diaphysenwinkel CCD (124° - 136°) | 134 | 139 |
| med, prox Femur-Tangenten-Winkel aMPFW (80°-89°) | 92 | 96 |
| lat, prox Femur-Tangenten-Winkel mLPFW (85°-95°) | 83 | 79 |
| anat, lat, dist Femur-Gelenk-Winkel aLDFW (79°-83°) | 84 | 82 |
| mech, lat, dist Femur-Gelenk-Winkel mLDFW (85°-90°) | 89 | 88 |
| med, prox, Tibia-Gelenk-Winkel MPTW (85°-90°) | 86 | 87 |
| lat, dist Tibia-Gelenk-Winkel LDTW (86°-92°) | 85 | 89 |
| anat, post, dist Femur-Gelenk-Winkel aPDFW (79°-87°) | | |
| anat, post, prox Tibia-Gelenk-Winkel aPPTW (77°-87°) | | |
| anat, ant, dist Tibia-Gelenk-Winkel aADTW (78°-82°) | | |

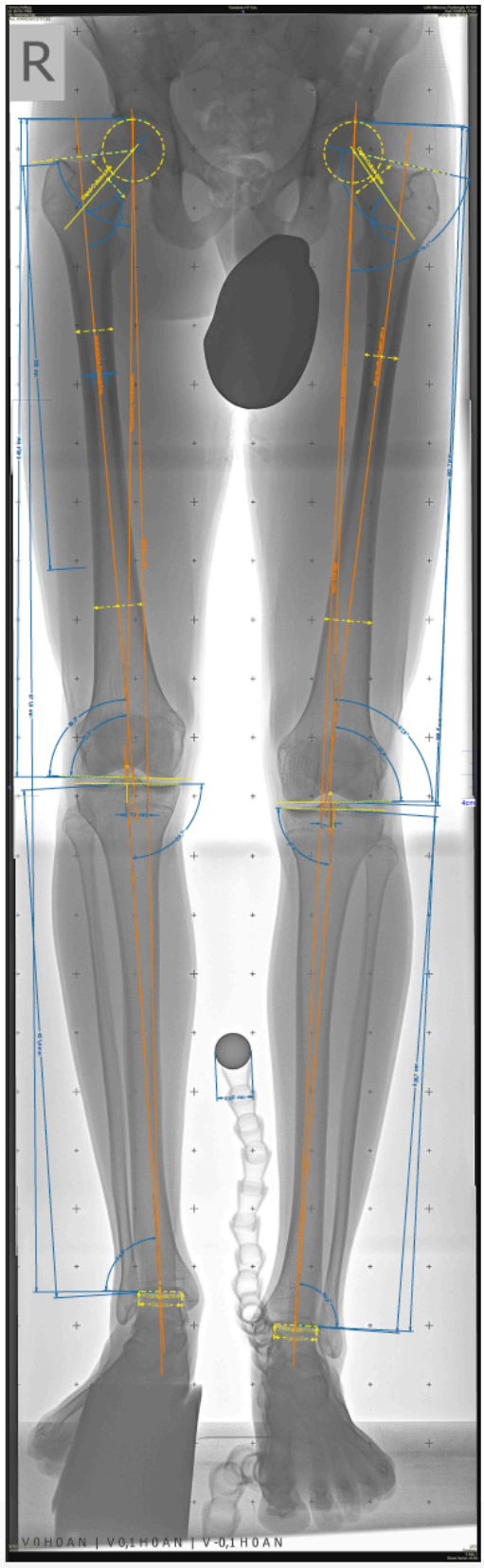
Beinlängendifferenz

| | |
|---|---|
| Differenz Oberschenkel (mm) | -19r |
| Differenz Unterschenkel (mm) | -8r |
| Gesamtdifferenz (mm) | -27r |
| Beckengeradstand bei... (mm) | |

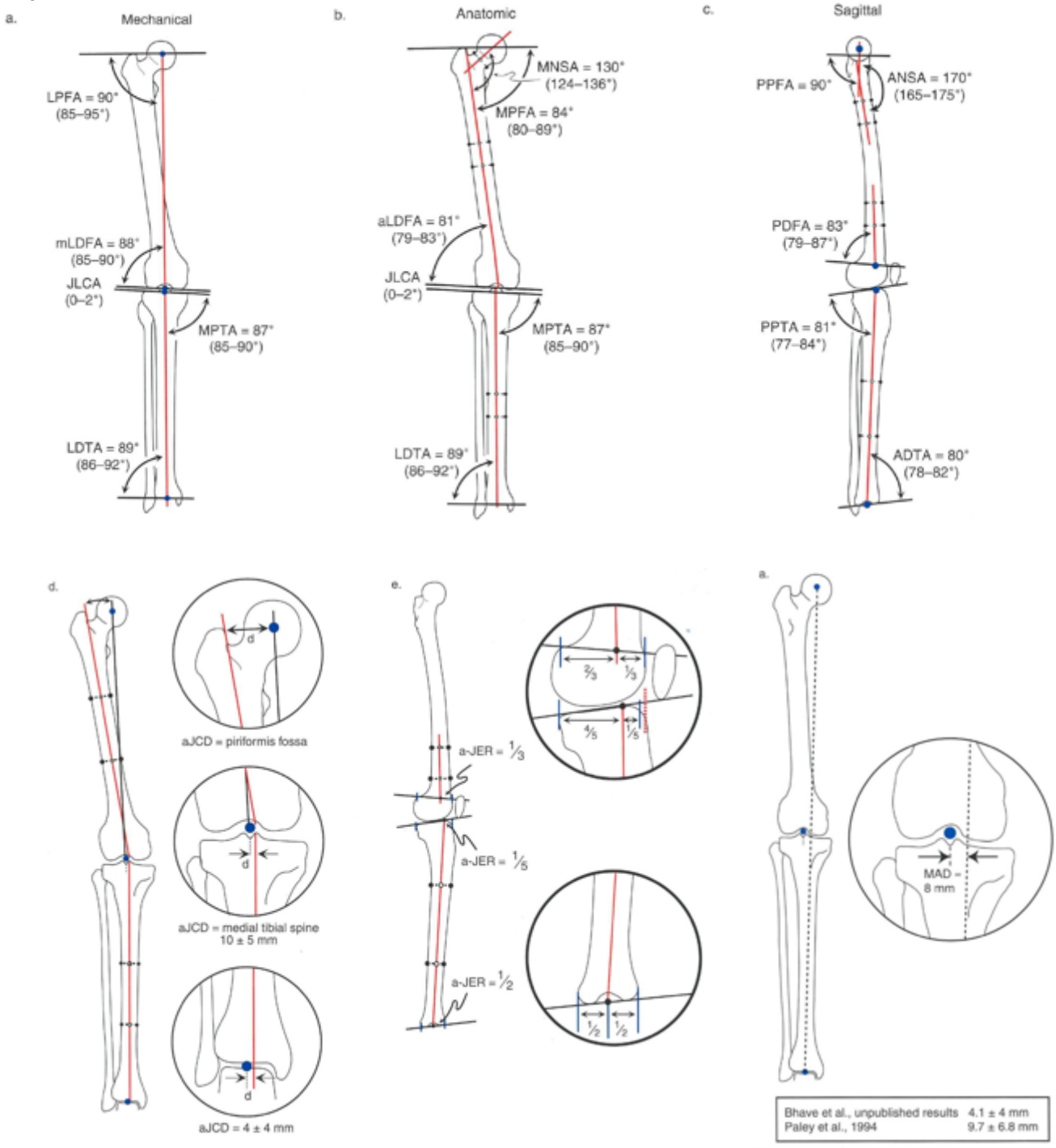
Beinlängen-CT mit Torsionsmessung

| | RE Bein | Ergebnis | LI Bein | Ergebnis |
|---|---|---|---|---|
| Anteversion Schenkelhals (+/-) | | | | |
| **SchenkelHalsAntetorsion SHA** [(-25) **+ 4 - +20** (+37)] | | | | |
| Stellung Condylen | | | | |
| **SprungGelenksAussentorsion SGA** [(0) **+10 - +30** (+48)] | | | | |
| Stellung Talusrolle | | | | |

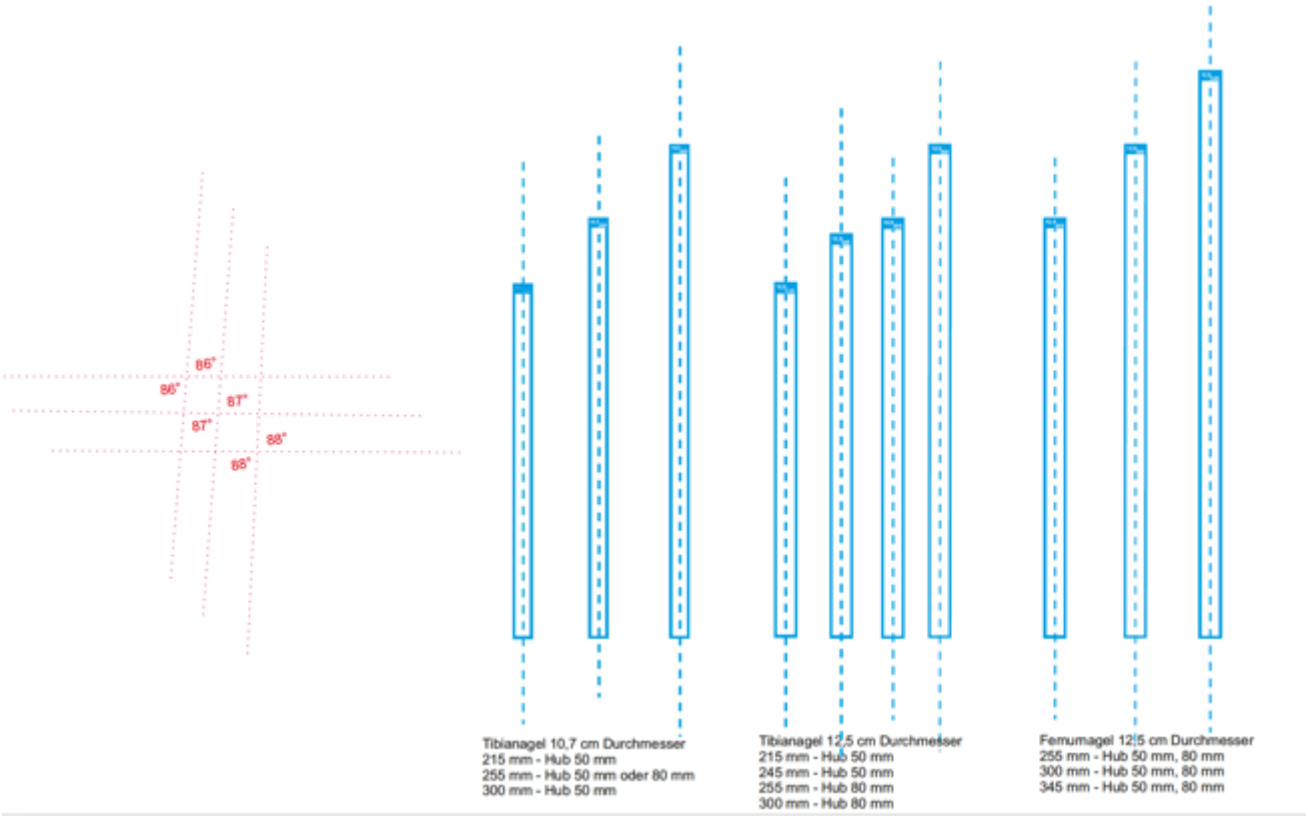
Bemerkungen:




- **Fig.3: Analysis result of the basic and relevant anatomical landmarks using professional graphic software (Corel Draw X4)**




- **Fig.4: Axes and joint angles from Paley, D. (2002). Principles of deformity correction (Berlin; New York: Springer).**




- **Fig.5: Templates for optional length, diameter and stroke of the implants (ISKD nail is the preliminary digital nail template) and physiologic knee joint angles (left side)- predesigned and available in the software for digital planning.**

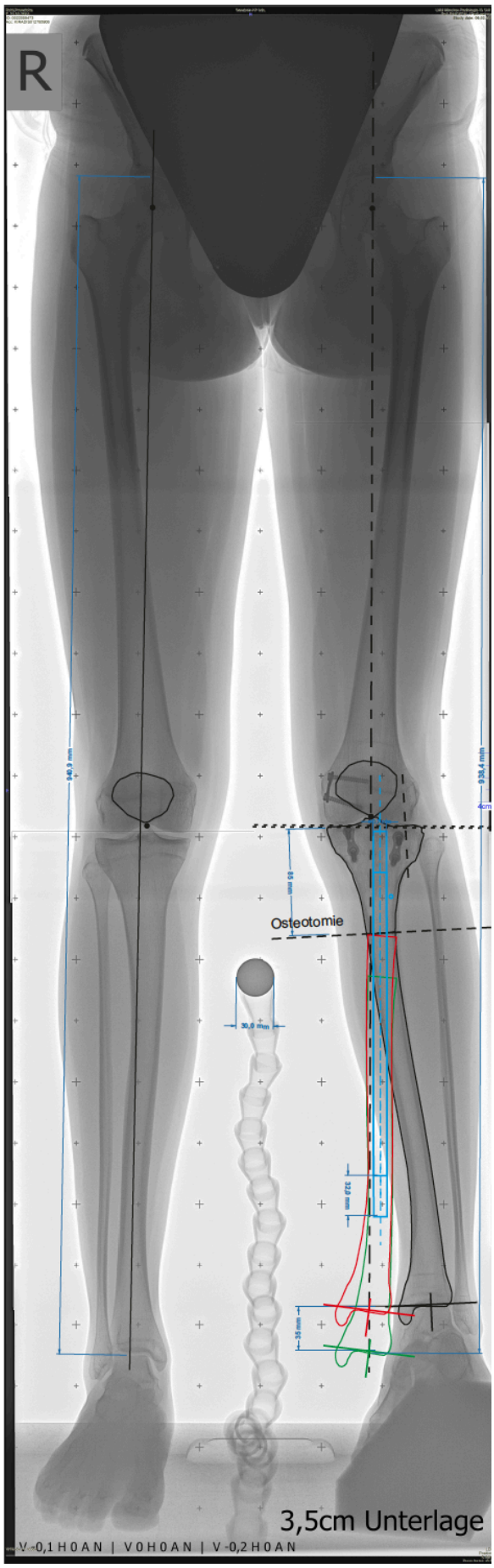



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**Fig.6: An Example of a complete digital surgical planning for operation (tibia)**

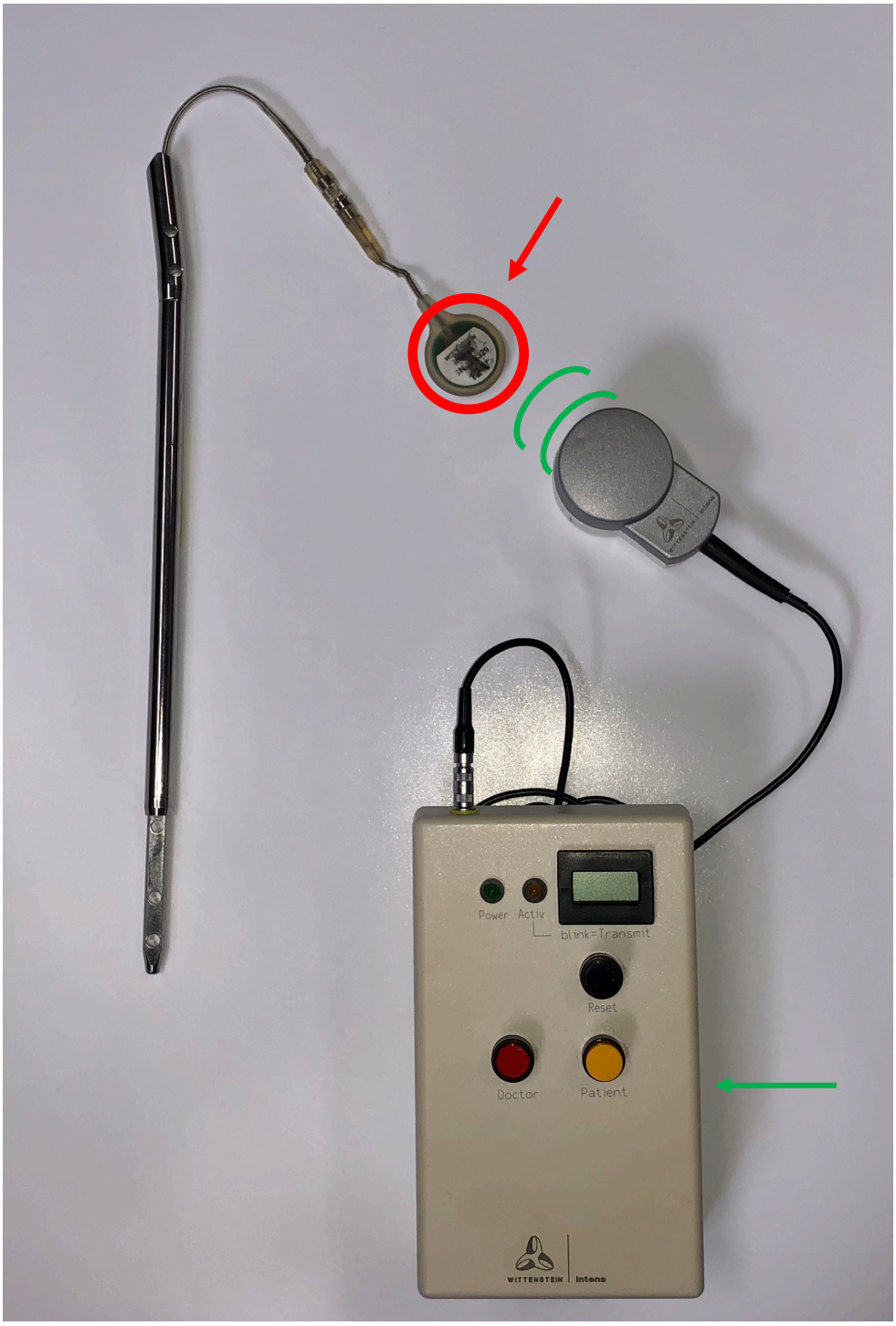


**Fig.7: Fitbone® nail apparatus**

TAA Nail with subcutaneous receiver (red arrow); Electric external controller (green arrow)

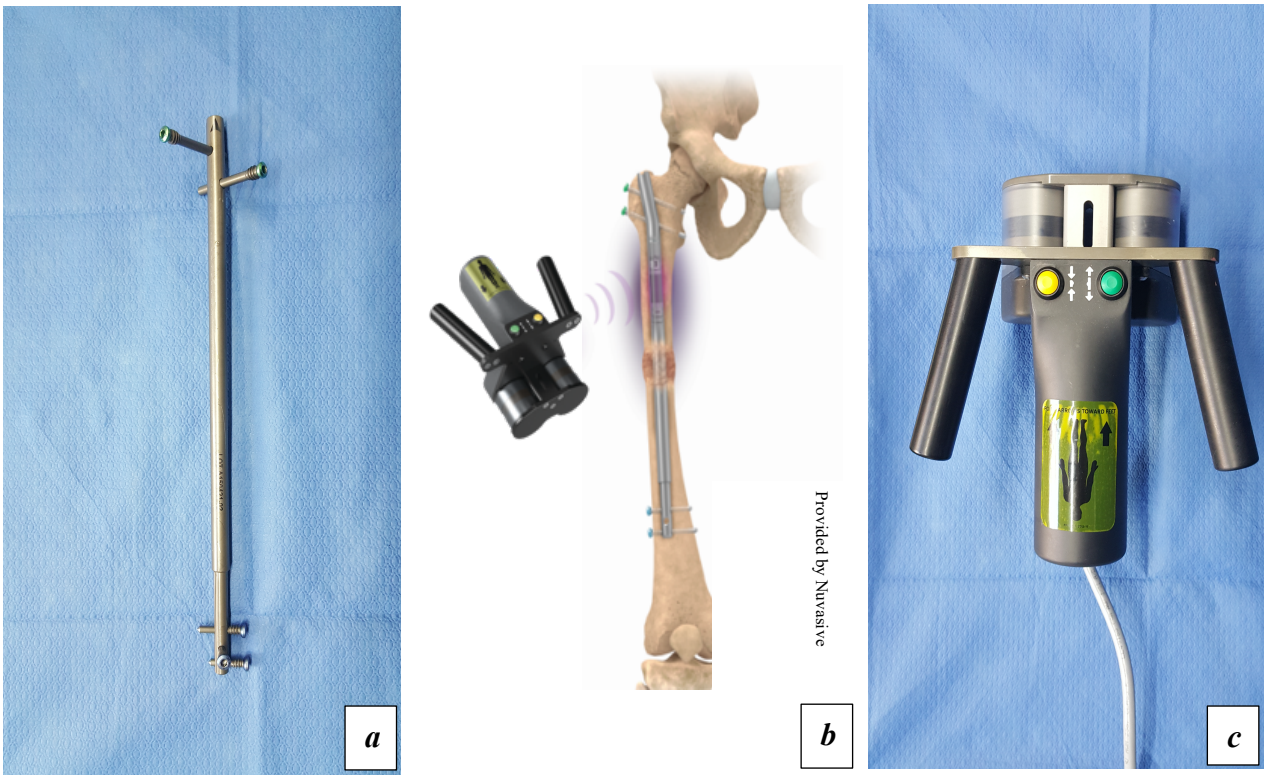


**Fig.8 PRECICE® nail system**

*Fig.8-a:* PRECICE® nail for tibia. *Fig.8-b, c:* Magnetic external remote controller

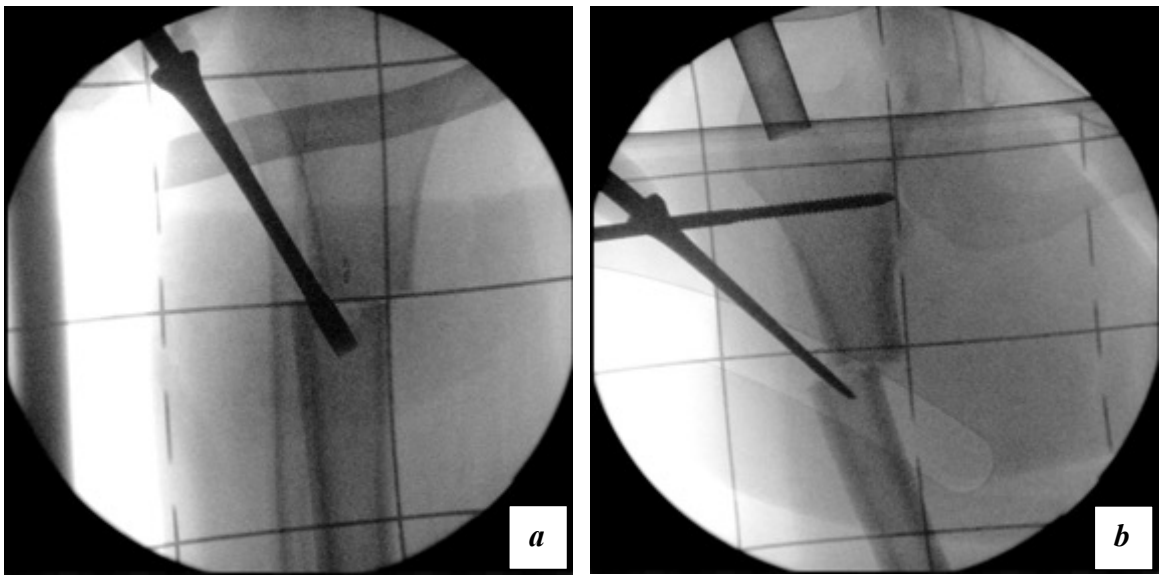


**Fig.9 Completion of a drill bit osteotomy under the x-ray image intensifier**

Fig.9-a: cutting through the remaining bridges with a chisel; Fig.9-b: completed osteotomy

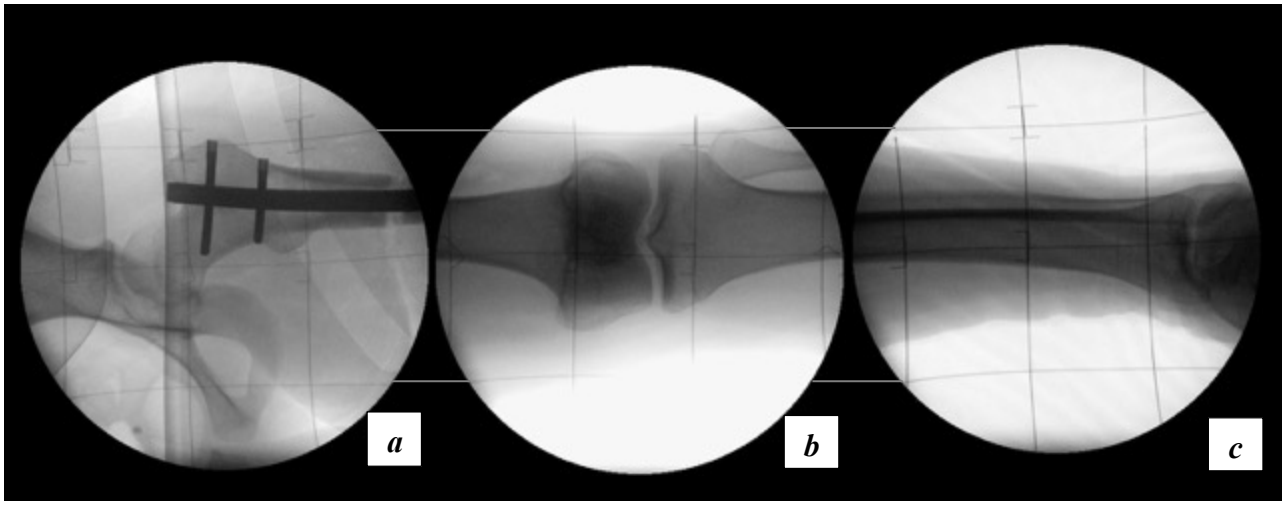


**Fig.10: Final intraoperative x-ray-grid control with image intensifier: Hip, knee and ankle joint centred on the same solid line of the x-ray grid**

Fig.10-a: the centre of the femoral head. Fig.10-b: the centre of the knee. Fig.10-c: the centre of the ankle.

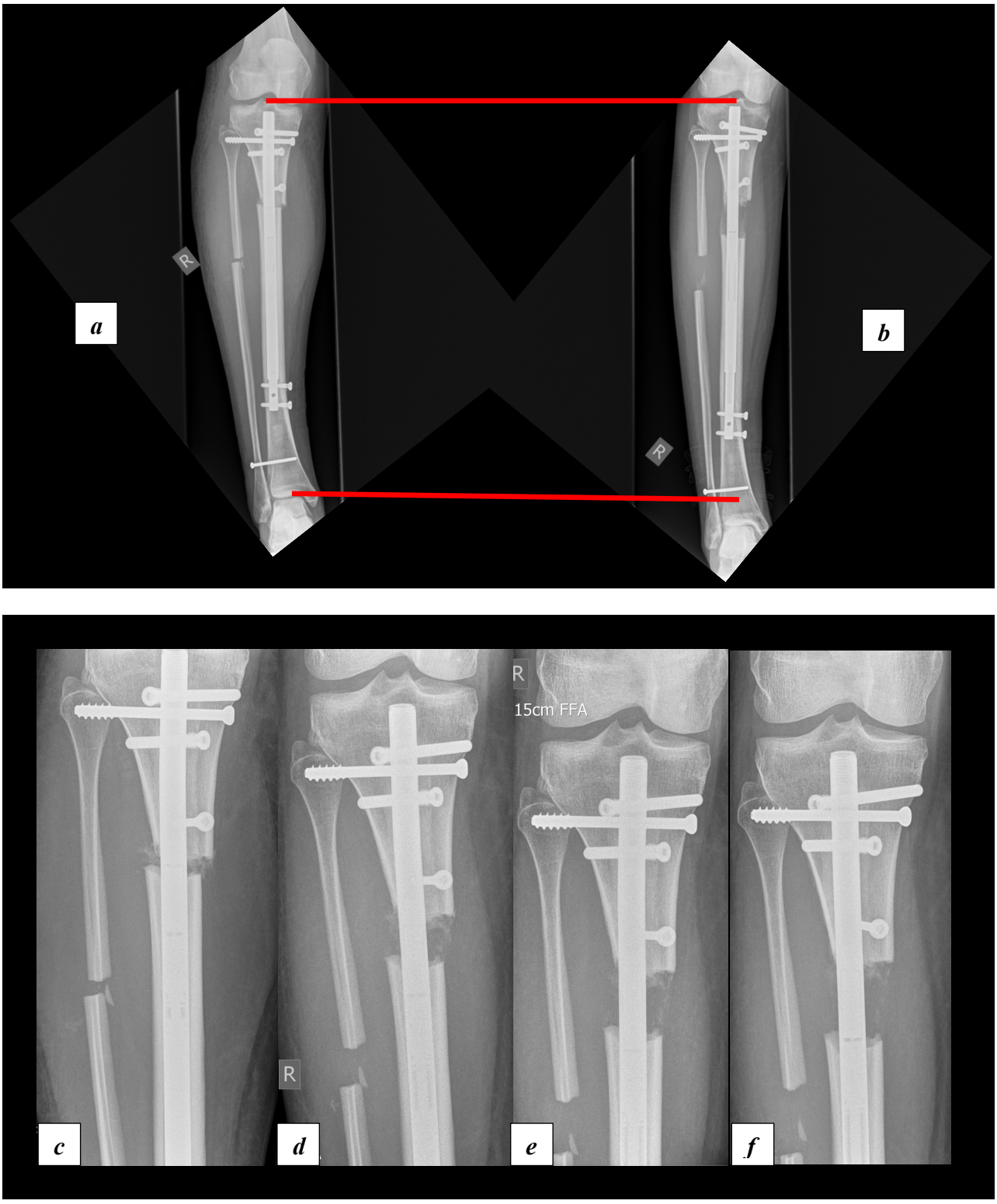


**Fig.11: The X-rays of the Distraction in Progress**

Fig.11-a: first day post OP. Fig.11-b: final lengthening result.

Fig.11-c: 7days post-OP. Fig.11-d: 14days post-OP. Fig.11-e: 21days post-OP. Fig.11-f: 28days post-OP.

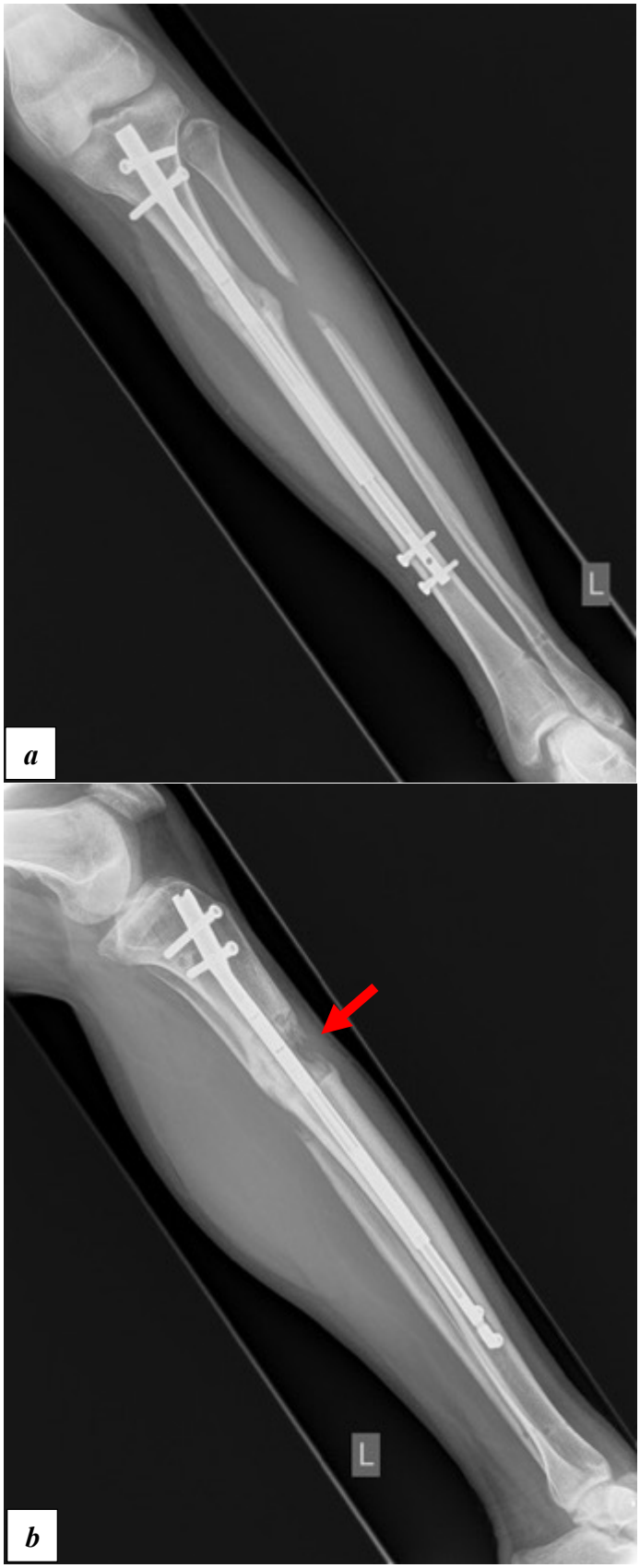


**Fig.12: An Example of Radiographic Consolidation**

Fig.12-a: anteroposterior consolidation. Fig.12-b: lateral consolidation

The regeneration of anterior tibia is the slowest (see arrow point)

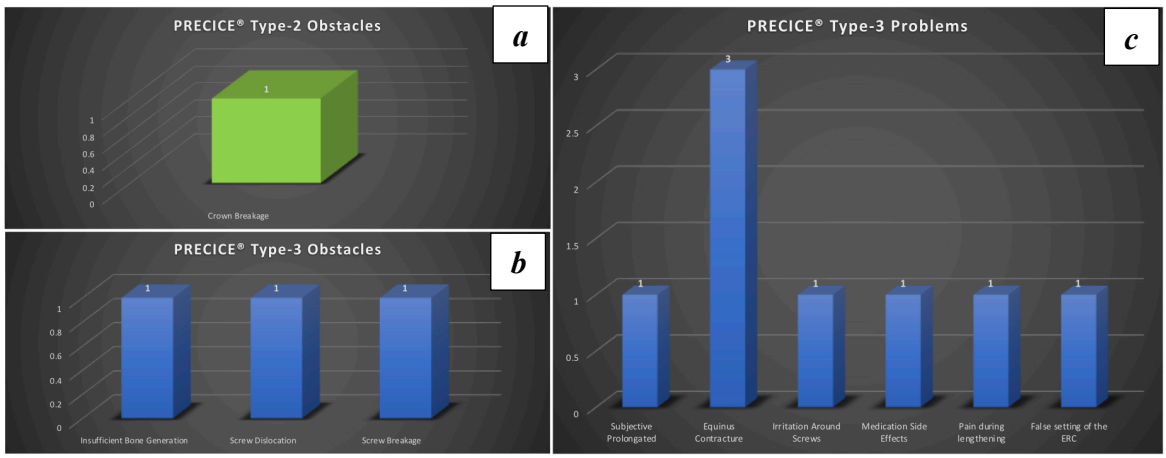


**Fig.13 Summery of complications from PRECICE® nail group**

Fig.13-a: Types-2 obstacle from PRECICE® nail group; Fig.13-b: Types-3 problems from PRECICE® nail group; Fig.13-c: Type-3 obstacles from PRECICE® nail group

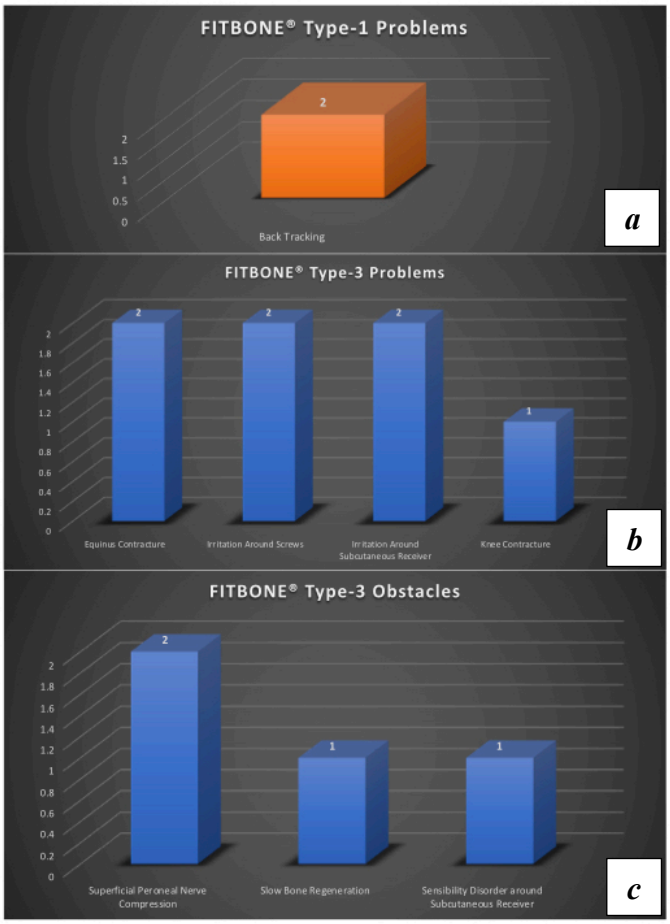


**Fig.14 Summery of complications from Fitbone® nail group**

Fig.14-a: Types-1 problems from Fitbone® nail group； Fig.14-b: Type-3 problem from Fitbone® nail group; Fig.14-c: Type-3 obstacles from Fitbone® nail group

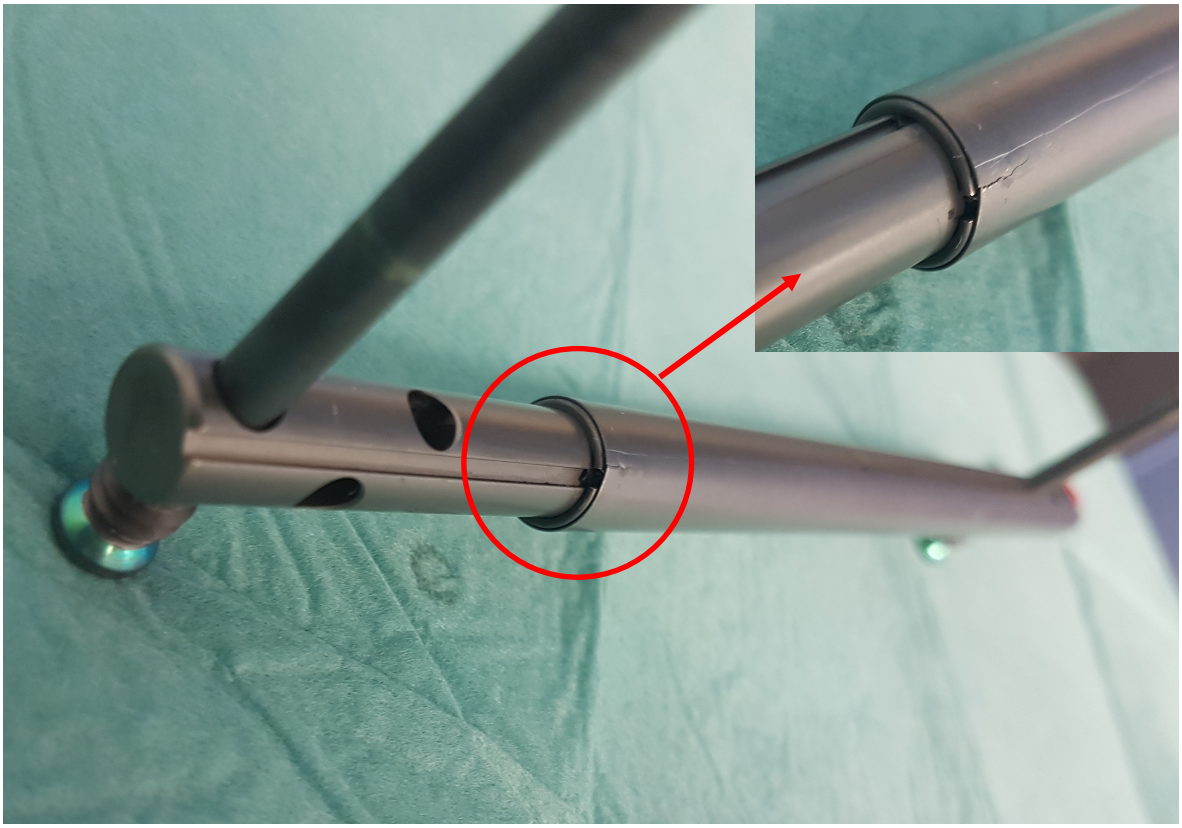

**Fig.15 Crown breakage of PRECICE® nail patient (P2)**

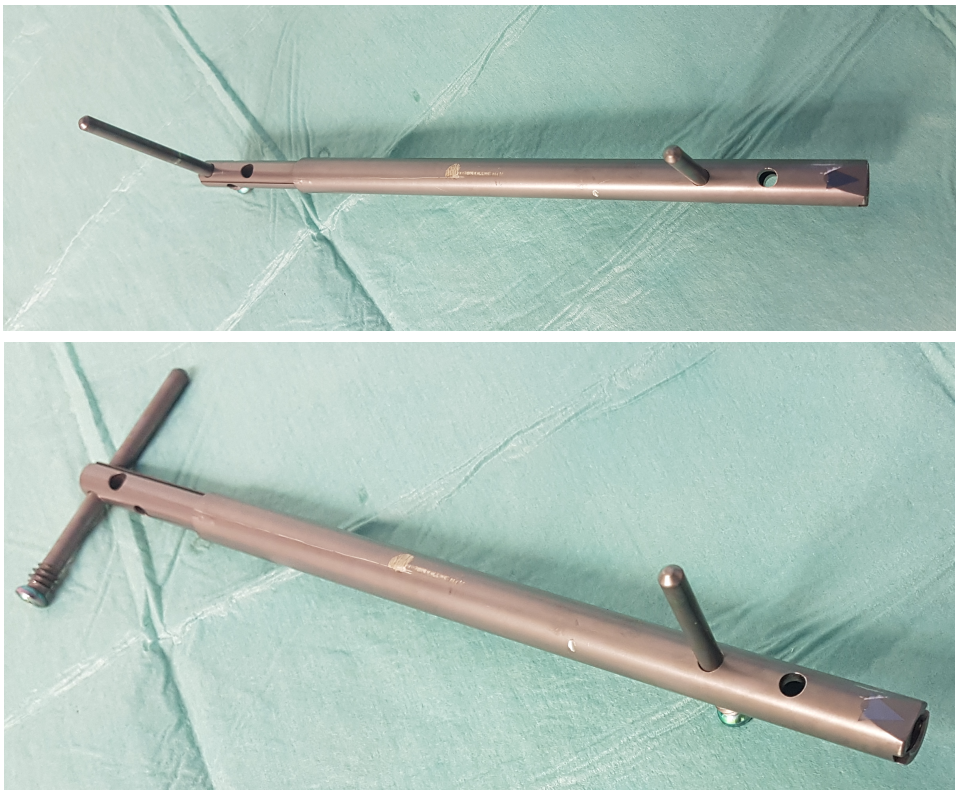

**Fig.16 The crown breakage caused instability of the anti-rotation mechanism of the PRECICE® nail**

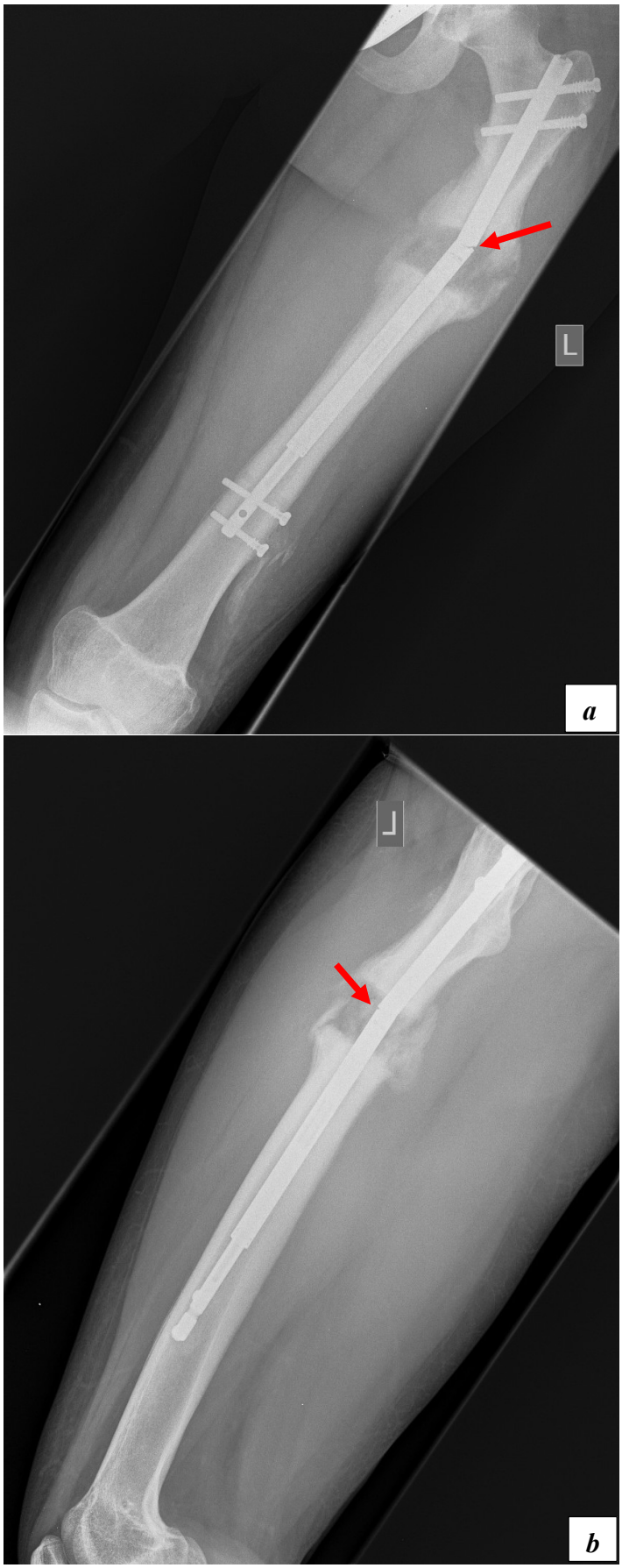


**Fig.17 Breakage of PRECICE® nail (P1)**

# 10. Curriculum Vitae

**Personal Information**

| | |
|---|---|
| Name: | Fuhuan CHEN |
| Birthday: | 28.02.1989 |
| Marital Status: | Single |
| Nationality: | China |
| Birth Place： | Yulin, China |

**Occupations**

| | |
|---|---|
| Since 01.2018 | 3D-Surgery, Department of General-, Trauma- and Reconstructive Surgery, University Hospital of Munich (LMU), Germany |
| 09.2016-07.2017 | Residency rotation in surgery department in Beijing Chaoyang Hospital |
| 07.2013-07.2016 | Residency rotation during master's degree in Chinese PLA Medical School |

**Educations**

Since 1.2018 Doctoral Degree in the university of LMU

Supervisor: Prof. Dr. E. Euler, Dr. P.H. Thaller, MSc

Doctoral Essay Title: A comparison of the complications and effectiveness of intramedullary limb lengthening – a matched pair analysis of two different lengthening systems (FITBONE®, PRECICE®)

07.2013-07.2016 Master's degree in the Chinese PLA Medical School

Supervisor: Prof. Dr. Song HF

Master Essay Title: Regulation of human epidermal stem cells differentiating into sweat gland cells by gene PRX-2.

07.2008-07.2013 Bachelor's degree in Qingdao University

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With all the nice people I had met in Germany, who had made my 3 years living in Munich a memorable and meaningful experience.

# 12. Publications

1. Thaller PH*, Fürmetz J*, **F. Chen**, Degen N, Manz KM, Wolf F: Bowlegs and intensive football training in children and adolescents—a systematic review and meta-analysis. Dtsch Arztebl Int 2018; 115: 401–8. Published, IF=4.46.
2. Degen N, Randeu T, Hilpert K, Linhart C, **F. Chen**, Wolf F, Fürmetz J, Euler E, Thaller PH, Preventive fasciotomy of the anterior compartment of the lower leg: Effects on strength and range of motion of dorsiflexion of the foot. Submitted, Injury, IF=2.1.
3. **F. Chen**, Kirsi M., Sebastian G., Wolf F., Böcker W., Thaller PH. Quality of Long Standing Radiograph for Limb Deformities：Assessment of the Patella Position. Submitting, JBJS IF=4.9.
4. **F. Chen**, F. Wolf F, Degen N, Fürmetz J, Thaller PH, Euler E. A comparison of the complications and effectiveness of intramedullary limb lengthening – a matched pair analysis of two different lengthening nails (FITBONE®, PRECICE®). Submitting, Injury. IF=2.1.

# 13. References


1. Giles, L.G., and Taylor, J.R. Low-back pain associated with leg length inequality. Spine. 1981; 6, 510–521.
2. Woerman, A.L., and Binder-Macleod, S.A. Leg Length Discrepancy Assessment: Accuracy and Precision in Five Clinical Methods of Evaluation. J. Orthop. Sports Phys Ther. 1984; 5, 230–239.
3. Maffulli, N., Longo, U.G., Spiezia, F., Denaro, V. Sports injuries in young athletes: long-term outcome and prevention strategies. Phys Sports med. 2010; 38, 29–34.
4. Guichet, J.M., Spivak, J.M., Trouilloud, P., Grammont, P.M. Lower limb-length discrepancy. An epidemiologic study. Clin. Orthop. Relat. Res. 1991; 235–241
5. Raczkowski, J.W., Daniszewska, B., Zolynski, K. Clinical research Functional scoliosis caused by leg length discrepancy. Aoms. 2010; 3, 393–398.
6. Gurney, B. Leg length discrepancy. Gait Posture. 2002; 15, 195–206.
7. Sheha ED, Steinhaus ME, Kim HJ, Cunningham ME, Fragomen AT, Rozbruch SR. Leg-Length Discrepancy, Functional Scoliosis, and Low Back Pain. JBJS Rev. 2018;6(8): e6.
8. Visuri T, Lindholm TS, Antti-Poika I, Koskenvou M. The role of overlength of the leg in aseptic loosening after total hip arthroplasty. Ital J Orthop. Traumatol. 1993; 19:107–11.
9. Brand RA Yack HJ. Effects of leg length discrepancies on the forces at the hip joint. Clin. Orthop. 1996; 333:172–80.
10. Gross, R.H. Leg length discrepancy: how much is too much? Orthopedics 1978; 1, 307–310.
11. Reid DC, Smith B. Leg length inequality: a review of etiology and management. Physiother. Can. 1984; 36:177–82.
12. Dexel J, Kirschner S, Günther K-P, Lützner J. Agreement between radiological and computer navigation measurement of lower limb alignment. Knee Surgery, Sports Traumatology, Arthroscopy. 2014; 22(11):2721-2727.
13. Babazadeh S, Dowsey MM, Bingham RJ et al. The long leg radiograph is a reliable method of assessing alignment when compared to computer-assisted navigation and computer tomography. Knee 2013; 20:242–249.
14. Stanitski, D.F. Limb-Length Inequality: Assessment and Treatment Options: Journal of the American Academy of Orthopaedic Surgeons 1999; 7, 143–153.

15. Jorge Gil-Albarova, Julio de Pablos, Marco Franzeb & José Cañadell. Delayed distraction in bone lengthening, Acta Orthopaedica Scandinavia 1992; 63:6, 604-606.
16. Moss, D.P., and Tejwani, N.C. Biomechanics of external fixation: a review of the literature. Bull NYU Hosp Jt. Dis. 2007; 65, 294–299.
17. Jauregui JJ, Bor N, Thakral R, Standard SC, Paley D, Herzenberg JE. Life- and limb-threatening infections following the use of an external fixator. The Bone & Joint Journal 2015; 97-B: 1296–300.
18. Eralp L, Kocaoglu M, Yusof NM, Bulbul M. Distal Tibial Reconstruction with Use of a Circular External Fixator and an Intramedullary Nail. J Bone Joint Surg Am. 2007; 89:2218-2224.
19. Paley D, Fleming B, Catagni M, Kristiansen T, Pope M. Mechanical evaluation of external fixators used in limb lengthening. Clin Orthop. Relat. Res 1990:50–7.
20. Kristiansen LP, Steen H. Lengthening of the tibia over an intramedullary nail, using the llizarov external fixator: Major complications and slow consolidation in 9 lengthenings. Acta Orthopaedica Scandinavica 1999; 70:271–4.
21. Wang Y, Jiang H, Deng Z, Jin J, Meng J, Wang J, et al. Comparison of Monolateral External Fixation and internal Fixation for Skeletal Stabilisation in the Management of Small Tibial Bone Defects following Successful Treatment of Chronic Osteomyelitis. BioMed Research International 2017; 2017:1–8.
22. Mahboubian S, Seah M, Fragomen AT, Rozbruch SR. Femoral Lengthening with Lengthening over a Nail has Fewer Complications than Intramedullary Skeletal Kinetic Distraction. Clin Orthop Relat Res 2012; 470:1221–31.
23. Lee, D.J., Schaffer, J., Chen, T., and Oh, I. Internal Versus External Fixation of Charcot Midfoot Deformity Realignment. Orthopedics 2016; 39, e595-601.
24. AL-Sayyad, M.J. Lower limb lengthening and deformity correction using the Fitbone motorized nail system in the adolescent patient: Journal of Pediatric Orthopaedics 2012; B 21, 131–136.
25. Guichet J-M, Deromedis B, Donnan LT, Peretti G, Lascombes P, Bado F. Gradual femoral lengthening with the albizzia intramedullary nail: The Journal of Bone and Joint Surgery-American Volume 2003;85:838–48.
26. Bliskunov AI. Intramedullary distraction of the femur (preliminary report). Ortop Travmatol Protez 1983:59–62.

27. Mazeau P, Assi C, Louahem D, L'Kaissi M, Delpont M., Cottalorda J. Complications of Albizzia femoral lengthening nail: an analysis of 36 cases. Journal of Pediatric Orthopaedics 2012; B21, 394–399.
28. Weber P., Hax PM., Betz, A. Ausgleich posttraumatischer Beinlängendifferenzen mit einem Verlängerungsmarknagel. Trauma Berufskrankh 2017; 19, 191–197.
29. Thaller P.H., Fürmetz J., Wolf F., Eilers T., Mutschler, W. Limb lengthening with fully implantable magnetically actuated mechanical nails (PHENIX (®))-Preliminary results. Injury 2014； 45 Suppl 1, S60-65.
30. Burghardt RD, Herzenberg JE, Specht SC, Paley D. Mechanical failure of the intramedullary skeletal kinetic distractor in limb lengthening. J Bone Joint Surg Br 2011; 93:639–43.
31. Cole JD, Justin D, Kasparis T, DeVlught D, Knobloch C. The intramedullary skeletal kinetic distractor (ISKD): first clinical results of a new intramedullary nail for lengthening of the femur and tibia. Injury 2001; 32:129–39.
32. Kenawey M, Krettek C, Liodakis E, Wiebking U, Hankemeier S. Leg lengthening using intramedullay skeletal kinetic distractor: Results of 57 consecutive applications. Injury. 2011; 42:150–5.
33. Lee DH, Ryu KJ, Song HR, Han S-H. Complications of the Intramedullary Skeletal Kinetic Distractor (ISKD) in Distraction Osteogenesis. Clin Orthop Relat Res 2014; 472:3852–9.
34. Betz A, Baumgart R, Schweiberer L. First fully implantable intramedullary system for callus distraction--intramedullary nail with programmable drive for leg lengthening and segment displacement. Principles and initial clinical results. Chirurg 1990; 61:605–9.
35. Accadbled F., Pailhé R., Cavaignac E., Sales de Gauzy, J. Bone lengthening using the Fitbone ® motorized intramedullary nail: The first experience in France. Orthopaedics & Traumatology: Surgery & Research 2016； 102, 217–222.
36. Baumgart R., Thaller P., Hinterwimmer S., Krammer M., Hierl T., Mutschler W. A Fully Implantable, Programmable Distraction Nail (Fitbone) — New Perspectives for Corrective and Reconstructive Limb Surgery. In Practice of Intramedullary Locked Nails, P.D.K.-S. Leung, D.G. Taglang, P.D.D.R. Schnettler, D.V. Alt, P.D.H.J.T.M. Haarman, D.H. Seidel, and P.D.I. Kempf, eds. (Springer Berlin Heidelberg), 2006; pp. 189–198.

37. Krieg A.H., Lenze U., Speth B.M., Hasler C.C. Intramedullary leg lengthening with a motorized nail: Indications, challenges, and outcome in 32 patients. Acta Orthopaedica 2011; 82, 344–350.
38. Paley D. PRECICE intramedullary limb lengthening system. Expert Rev Med Devices 2015; 12:231–49.
39. S.R. Rozbruch, R.C. Hamdy (Eds.), Limb Lengthening and Reconstruction Surgery Case Atlas, Springer International Publishing, Switzerland (2015), pp. 27-31.
40. Nasto L.A., Coppa V., Riganti S., Ruzzini L., Manfrini M., Campanacci L., Palmacci O., Boero S. Clinical results and complication rates of lower limb lengthening in paediatric patients using the PRECICE 2 intramedullary magnetic nail: a multicentre study. Journal of Pediatric Orthopaedics 2020; B1.
41. Wagner P., Burghardt R.D., Green S.A., Specht S.C., Standard S.C., Herzenberg J.E. PRECICE® magnetically driven, telescopic, intramedullary lengthening nail: pre-clinical testing and first 30 patients. SICOT-J 2017; 3, 19.
42. Thaller P.H., Degen N., Fürmetz J., Wolf F. Längen-, Achs- und Torsionskorrekturen mit Distraktionsmarknägeln: Erfahrungen mit 5 verschiedenen Systemen. Trauma Berufskrankh 2017; 19, 182–190.
43. Li P., Tao F., Song W. et al. External fixation-assisted reduction for the treatment of neglected hip dislocations with limb length discrepancy: a retrospective study of 13 cases. BMC Musculoskelet Disord 2019; 20, 621.
44. 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; 79:1464–1480.
45. Salcedo Cánovas C. Tibial bone lengthening via external fixation: Comparative study of the traditional technique and a technique with intramedullary nail assistance. Rev Esp Cir Ortop Traumatol. 2018; 62:8–18.
46. Xu W. Comparison of Intramedullary Nail versus Conventional Ilizarov Method for Lower Limb Lengthening: A Systematic Review and Meta-Analysis. Orthop Surg. 2017; 9:159–66.
47. Fragomen AT, Kurtz AM, Barclay JR, Nguyen J, Rozbruch SR. A Comparison of Femoral Lengthening Methods Favors the Magnetic internal Lengthening Nail When Compared with Lengthening Over a Nail. HSS Jrnl. 2018; 14:166–76.
48. Sun X-T, Easwar TR, Manesh S, Ryu J-H, Song S-H, Kim S-J, et al. Complications and outcome of tibial lengthening using the Ilizarov method with or without a

supplementary intramedullary nail: A CASE-MATCHED COMPARATIVE STUDY. The Journal of Bone and Joint Surgery British Volume 2011; 93-B: 782–7.

49. Guo Q, Zhang T, Zheng Y, Feng S, Ma X, Zhao F. Tibial lengthening over an intramedullary nail in patients with short stature or leg-length discrepancy: a comparative study. International Orthopaedics (SICOT) 2012; 36:179–84.
50. Burghardt RD, Manzotti A, Bhave A, Paley D, Herzenberg JE. Tibial lengthening over intramedullary nails: A matched case comparison with Ilizarov tibial lengthening. Bone and Joint Research 2016; 5:1–10.
51. Horn J, Grimsrud Ø, Dagsgard AH, Huhnstock S, Steen H. Femoral lengthening with a motorized intramedullary nail: A matched-pair comparison with external ring fixator lengthening in 30 cases. Acta Orthopaedica 2015; 86:248–56.
52. Rozbruch SR, Kleinman D, Fragomen AT, Ilizarov S. Limb Lengthening and Then Insertion of an Intramedullary Nail: A Case-matched Comparison. Clin. Orthop. Relat. Res. 2008; 466:2923–32.
53. Paley D. Problems, obstacles, and complications of limb lengthening by the Ilizarov technique. Clin Orthop. 1990; 81–104.
54. Lee DH, Kim S, Lee JW, Park H, Kim TY, Kim HW. A Comparison of the Device-Related Complications of Intramedullary Lengthening Nails Using a New Classification System. BioMed Research International 2017; 2017:1–9.
55. Liantis P., Mavrogenis A.F., Stavropoulos N.A., Kanellopoulos A.D., Papagelopoulos PJ., Soucacos P.N., Babis, G.C. Risk factors for and complications of distraction osteogenesis. Eur J Orthop Surg Traumatol. 2014; 24, 693–698.
56. Thaller P.H., Baumgart R., Burghardt R., Knuellig S., Buerklein D., Mutschler W. Digital imaging in lower limb bone deformities–standards and new perspectives. In Elsevier International Congress Series 1281, 2005; pp. 154–158.
57. Thaller, P.H., S. Weidert, P. Delhey. „Planning of lower deformity correction withprofessional graphic software (Corel DRAW Graphic Suite x4) “. In Programme and Abstracts Book. Barcelona, 2010.
58. Moreland J.R., Bassett L.W., Hanker, G.J. Radiographic analysis of the axial alignment of the lower extremity. The Journal of Bone & Joint Surgery 1987; 69, 745–749.
59. Mikulicz J. Die seitlichen Verkrümmungen am Knie und deren Heilungsmethoden. Arch. f klin Chir. 1879; 23:560-630.

60. Paley, D., Tetsworth, K. Mechanical axis deviation of the lower limbs: preoperative planning of uniapical angular deformities of the tibia or femur. Clinical Orthopaedics and Related Research 1992; 280, 48–64.
61. Singh, S., Lahiri, A., Iqbal, M. The results of limb lengthening by callus distraction using an extending intramedullary nail (Fitbone) in non-traumatic disorders. J Bone Joint Surg Br 2006; 88, 938–942.
62. Thaller, P.H., Wolf, F., Kucukkaya, M. Surgical Techniques for Lengthening and Deformity Correction of the Tibia with Lengthening Nails: Techniques in Orthopaedics 2014; 29, 150–157.
63. Fürmetz, J., Schuster, N., Wolf, F., Thaller, P.H. Lengthening of the humerus with intramedullary lengthening nails—preliminary report. Strategies in Trauma and Limb Reconstruction 2017; 12, 99–106.
64. Hankemeier S, Pape H-C, Gosling T, Hufner T, Richter M, Krettek C. Improved comfort in lower limb lengthening with the intramedullary skeletal kinetic distractor. Archives of Orthopaedic and Trauma Surgery 2004; 124:129–33.
65. Schiedel FM, Vogt B, Tretow HL, Schuhknecht B, Gosheger G, Horter MJ, et al. How precise is the PRECICE compared to the ISKD in intramedullary limb lengthening? Reliability and safety in 26 procedures. Acta Orthopaedica 2014; 85 (3) :293-298.
66. Leidinger B, Winkelmann W, Roedl R. Limb lengthening with a fully implantable mechanical distraction intramedullary nail[J]. Zeitschrift für Orthopädie, 2006, 144(4):419-426.
67. Thaller P.H., Zoffl F., Delhey P., Comparison between fully implantable motorized and mechanical distraction nails - a matched-pairs study, in: J Child Orthop. Presented at the ASAMI 2011, Barcelona, 2011. pp. 373–386.
68. Guer JL., Blanchard S., Harnagea M., Lopez E., Behr M. Does Intensive Soccer Playing During the Growth Period Lead to Leg Length Discrepancies? Sports Med Int Open 2017; 1, E183–E187.
69. Gurney, B., Mermier, C., Robergs, R., Gibson, A., Rivero, D. Effects of Limb-Length Discrepancy on Gait Economy and Lower-Extremity Muscle Activity in Older Adults: The Journal of Bone and Joint Surgery-American Volume 2001; 83, 907–915.
70. Watanabe K., Tsuchiya H., Yamamoto N., Shirai T., Nishida H., Hayashi K., Takeuchi A., Matsubara H., Nomura I. Over 10-year follow-up of functional outcome in patients with bone tumors reconstructed using distraction osteogenesis. Journal of Orthopaedic Science 2013; 18, 101–109.

71. Noonan KJ, Leyes M, Forriol F, Ca.adell J. Distraction osteogenesis of the lower extremity with use of monolateral external ixation. A study of two hundred and sixty-one femora and tibiae. J Bone Joint Surg Am. 1998; 80(6): 793-806.
72. Chan, G.K., and Duque, G. Age-Related Bone Loss: Old Bone, New Facts. Gerontology 2002; 48, 62–71.
73. Koczewski P., Shadi M. Factors influencing bone regenerate healing in distraction osteogenesis. Ortop Traumatol Rehabil. 2013; 15, 591–599.
74. Dahl M.T., Gulli B., Berg T. Complications of limb lengthening. A learning curves. Clin. Orthop. Relat. Res. 1994; 10–18.
75. Kunze K., Hofstetter H., Posalaky I. et al. Veränderungen der Knochen durch blutung nach Osteotomien und osteosythesen. Unfallchirurgie 1981; 7,169-180.
76. Fischgrund J.; Paley D.; Suter C: Variables affecting time to bone healing during limb lengthening. Clin. Orthop. 1994; 301: 31-37.
77. Lee J.J., Patel R., Biermann J.S., Dougherty P.J. The Musculoskeletal Effects of Cigarette Smoking: The Journal of Bone & Joint Surgery 2013; 95, 850–859.
78. Zheng L.W., Ma L., Cheung L.K. Changes in blood perfusion and bone healing induced by nicotine during distraction osteogenesis. Bone 2008; 43, 355–361.
79. Caton J., Dumont P., Berard J., Michel C.R. Intermediate results of a series of 33 cases of leg lengthening using H. Wagner's technic. Rev Chir Orthop Reparatrice Appar Mot 1985; 71 Suppl 2, 44–48.
80. Popkov A.V. Errors and complications of operative lengthening of the lower extremities in adults by the Ilizarov method. Vestn. Khir. Im. I. I. Grek. 1991; 146, 113–116.
81. Donnan L.T., Saleh M., Rigby A.S. Acute correction of lower limb deformity and simultaneous lengthening with a monolateral fixator. J Bone Joint Surg. Br. 2003; 85, 254–260.
82. Lascombes P., Popkov D., Huber H., Haumont T., Journeau P. Classification of complications after progressive long bone lengthening: proposal for a new classification. Orthop. Traumatol Surg. Res 2012; 98, 629–637.
83. Kenawey M., Krettek C., Liodakis E., Meller R., Hankemeier S. Insufficient bone regenerate after intramedullary femoral lengthening: risk factors and classification system. Clin. Orthop. Relat. Res. 2011; 469, 264–273.
84. Dinçyürek H., M., Kocaoğlu I. L., Eralp F.E., Bilen, G., Dikmen, I. Eren. „Functional results of lower extremity lengthening by motorized intramedullary nails ". Acta orthopaedica et traumatologica turcica 2012; 46, Nr. 1, 42–49.

85. Krieg A.H., B.M. Speth, B.K. Foster. „Leg lengthening with a motorized nail in adolescents: an alternative to external fixators? “. Clinical Orthopaedics and Related Research 2008; 466, 189–97.
86. Panagiotopoulou V.C., Davda K., Hothi H.S., Henckel J., Cerquiglini A., Goodier W.D., Skinner J., Hart A., Calder P.R. A retrieval analysis of the PRECICE intramedullary limb lengthening system. Bone & Joint Research 2018; 7, 476–484.
87. Balemane, S., Adham, M. Prospective study of treatment of non-union of tibia using limb reconstruction system with intramedullary nailing. Jemds 2016; 5, 5091–5095.
88. Wraighte P.J., Scammell B.E. Principles of fracture healing. Surgery (Oxford) 2006; 24, 198–207.
89. Van Roermund P.M., Hoekstra A., Ter Haar Romeny B.M., Renooij, W. Bone healing during lower limb lengthening by distraction epiphysiolysis. J. Nucl. Med. 1988; 29, 1259–1263.