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Review Article

The Evolution of Limb Lengthening: A Historical Review and Modern Ethical Considerations

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Abstract

The realm of limb lengthening has undergone significant evolution, propelled by advancements in surgical methodologies and technologies. This article delves into the historical progression of limb lengthening procedures, tracing their origins back to the 19th century. Early techniques emerged as solutions for addressing diverse challenges such as war-related injuries, improperly healed fractures, and deformities, laying the groundwork for contemporary approaches. The evolution of external fixation devices and recent strides in internal lengthening technologies have collectively propelled limb lengthening into a highly sophisticated practice. Notably, the applications of limb lengthening have expanded beyond remedying pathological conditions to encompass cosmetic enhancements, amplifying the prominence of ethical considerations in contemporary discussions surrounding this medical discipline.

Key words: exclusive breastfeeding; knowledge; instruction; feeding; breastfeeding; breastfeeding techniques

Introduction

The field of limb lengthening has made progress in recent years with the introduction and utilization of various devices and technologies that increase the application of core biomedical principles [1]. Leg lengthening techniques have a rich historical lineage dating back to the 19th century when pioneering researchers sought innovative methods to address the challenges posed by war injuries, improperly healed fractures, and deformities [2]. These early efforts laid the foundation for the modern practices of limb lengthening and deformity correction. During the past century, the reasons for pursuing leg lengthening procedures have changed from primarily addressing issues like leg length disparities and deformities caused by poliomyelitis, wartime injuries, osteomyelitis, and poorly healed fractures to now encompassing congenital issues and considerations related to aesthetics [3]. Limb lengthening is a complex and prolonged procedure that extends beyond the operating room [4]. This article will discuss and describe the evolution of limb-lengthening techniques and procedures.

Leg lengthening techniques have a historical origin dating back to the 19th century, with pioneering researchers like von Langenbeck, Hopkins and Penrose, and von Eiselsberg meticulously documenting a wide array of methods, mostly centered around one-stage lengthening osteotomies [5]. These methods were developed as a result of difficulties in managing the consequences of war injuries, improperly healed fractures of the femoral shaft, and deformities resulting from post-polio syndrome [5]. One of the earliest innovators in introducing the concept of osteosynthesis was Bernhard Von Langenbeck. In 1852, he introduced the first osteosynthesis device in a patient suffering from pseudoarthrosis. He used two steel screws and an iron rim to stabilize two fragments of a non-union fracture of the humerus [6,7]. In 1864, Hopkins and Penrose recorded groundbreaking experiments that incorporated antiseptic measures on animals. These experiments evaluated the suitability of foreign bone for fixation and the subsequent changes that occurred when it interacted with living bone tissue [8]. These experiments concluded that when sterilized deceased bone comes into contact with living bone, it undergoes a process of organization. This process occurs between the fifth and eighth week and does not involve any inflammatory reactions. Additionally, when foreign bone is used for fixation and leads to the union of fractures, it gradually assimilates into the surrounding bone, eventually losing its distinct identity and disappearing [8]. Moving into the 20th century, von Eiselsberg, in 1906, introduced a range of surgical techniques for extending the length of the mandible. However, it wasn't until 1921 that this procedure was carried out by Bruhn. Bruhn's approach involved a vertical osteotomy on the mandible's body, followed by a bone grafting procedure [9].

Codivilla's Contributions

Limb lengthening as we know now began to take shape when Italian surgeon Alessandro Codivilla published a groundbreaking paper titled "On the Methods of Extending the Lower Limbs, Muscles, and Tissues Affected by Poliomyelitis Deformities" in 1905. In his publication, Codivilla outlined a method for lengthening shortened lower limbs in individuals with polio-related deformities. Codivilla introduced two distinct approaches. For minor limb length discrepancies, he recommended a technique involving rapid and forceful lengthening aided by narcotic medications [10]. Conversely, for more substantial length discrepancies, he introduced a method known as "continuous extension." This involved applying gentle traction with a pin inserted into the calcaneus [10]. He performed an oblique osteotomy in the femur using a chisel, followed by the application of moderate traction (25 to

30 kg). Subsequently, he immobilized the patient using a "plaster jacket" that covered the thorax, pelvis, and leg, securing the calcaneal pin in place. If the desired lengthening wasn't achieved, he would gradually cut the cast at the osteotomy site and apply additional traction in stages, not exceeding 25 to 30 kg per stage. This approach allowed for the desired lengthening to be achieved within 20 days, with the possibility of extending it to 30 to 35 days without experiencing pin-related complications [10]. Codivilla reported on the outcomes of his treatment in 26 patients who had limb shortening due to various reasons. All these patients successfully attained the intended lengthening, with the increase ranging from 3 to 8 centimeters [10-11]. However, the technique was not without its challenges, as complications such as significant nerve injuries, skin issues, and uncontrollable persistent seizures were observed [10-12]. Nevertheless, despite these complications, Codivilla noted that the method yielded highly favorable results, effectively correcting deformities and reducing or eliminating limb shortening [10]. Codivilla's method was widely spread and put into practice across both the United States and Europe. [11]

Magnuson was the pioneer in transforming Codivilla's techniques into experimental investigations [13]. In 1913, Magnuson authored a research paper detailing his experimental approach to single-stage femur lengthening, employing a step-cut osteotomy. He found that applying a force of 32 pounds was adequate to extend a dog's femur by ¼ to ½ inch [14]. To sustain the length, immediate fixation with ivory screws was employed. In another publication, Magnuson documented fourteen instances of femoral lengthening in humans using this method. Traction was applied for twenty to thirty minutes using a Hawley table. Among these patients, all experienced shock both before and after the surgery, temporary toe drop occurred in three cases, and tragically, one patient succumbed to shock [13,14]. He was the first surgeon to promote the adoption of a Z-shaped osteotomy following the creation of multiple drill holes and longitudinal splitting of the periosteum. This approach later became the established and accepted technique. He emphasized that this specific osteotomy method inflicted minimal harm to both the periosteum and endosteum, while also recognizing its biological potential [13]. Magnuson conducted bone lengthening of 5 to 7 cm in a single session and subsequently secured the divergent branches of the Z-shaped osteotomy using ivory screws to preserve the leg's extended length. [13]

In 1913, Ombredanne pioneered the use of an external fixation device to extend limbs [15,16]. He employed a gradual approach to lengthen the femur, adding 5 mm per day for 8 days, ultimately achieving a 4 cm increase in length [16]. He secured one pin above and another below the osteotomy using a device attached to the side of the thigh [16]. Unfortunately, this procedure often led to the development of osteomyelitis, and as a result, the technique was quickly discontinued [17].

Vittorio Putti and The Osteoton

Vittorio Putti took over as the director of the Rizzoli Institute of Bologna in 1912 following Codivilla's passing [18]. In 1921, Putti published a paper titled "Operative Lengthening of the Femur" and delivered a lecture to the American Medical Association in Boston where he reported the use of traction and counter traction applied directly to the femur [19,13]. His device involved inserting two metal pins into the proximal and distal fragments of the femur, penetrating both cortices without the need for predrilling [19,20]. These pins extended only on the outer side of the limb and were connected by a spring-loaded telescopic tube "the osteoton". No additional external fixation was used until the elongation process was complete, at which point the entire limb was immobilized with a plaster spica [19,20].

However, this method faced challenges in maintaining alignment and experienced some delays in bone union due to the insufficiently rigid apparatus. Moreover, as the force increased, the pins tended to pull out of the bones [19,13]. Consequently, Putti abandoned this technique and developed an apparatus for forceful skeletal traction using piano wire, coupled with a stationary extension device attached to the patient's bed [19,13]. Following this procedure, the limb was immobilized with plaster [13].

In addition to using bone lengthening during childhood, Putti applied this technique to correct shortening in adults with irreducible congenital hip dislocations, especially those who had previously undergone a Lorenz bifurcation osteotomy [19]. He also employed it in a case where femur shortening resulted from extensive damage to the femur's head and neck following a tuberculous hip condition [19].

Putti wasn't the first to employ wires for limb lengthening. The use of wires for this purpose was initially introduced by Klapp in 1913 during the Balkan War [13,21]. In 1918, Herzberg advanced this technique by applying traction to wires using a frame, demonstrating that this approach could be sustained for a substantial duration without resulting in infections [13,21]. These devices allowed surgeons to manipulate the bone fragments as needed and achieve axial corrections [13,21].

Advancements in the United States

Following the attendance of Putti's 1921 lecture, Abbott and Crego adopted the Osteoton and initiated limb-lengthening surgeries in St. Louis in 1924 [13]. Abbott addressed the primary limitation of the Osteoton, which was its one-sided fixation by using drill wires inserted proximally and distally to the osteotomy encompassing the entire cross-section of the tibia [22]. They improved the design by connecting these wires on both sides to telescopic tubes or threaded rods, creating a more stable frame structure. The steps of Abbott's operation involved lengthening the Achilles tendon, conducting an osteotomy of the fibula, inserting Steinmann pins into the proximal and distal ends of the tibia, followed by a tibial osteotomy, and then applying the distraction apparatus. He also made sure to completely divide the periosteum around the bone and the deep fascia on the anterolateral aspect of the leg [17]. The procedure involved an intraoperative distraction of 1 to 2 cm immediately after performing the osteotomy. After a waiting period of 7 to 10 days post-surgery, he commenced a gradual distraction at a rate of 1.5 to 3 cm per day [22]. Initially, in his first series of six cases, he advised against lengthening the tibia by more than two inches. However, over time, many surgeons have achieved greater increases in length [17]. Abbott introduced a method for tibial elongation that, with some modifications, became a standard procedure in the United States [20].

By the 1930s, Abbott and Crego had executed the surgery on 73 patients; however, he observed numerous complications [22]. Equinovalgus deformity of the foot occurred due to an uneven elongation of soft tissue in the lower leg and a disconnection in the tibiofibular joint [5,13,22]. They also witnessed limited mobility in the hip joint, flexion contractures in the knee joint, bending or twisting of the separated tibial fragments, weakening of the lower limb muscles, paralysis of the peroneal or tibial nerves, infections at the insertion site of pins, tissue death from pressure, both aseptic and septic necrosis of the fragments with severe bone inflammation, and delayed fractures [5,13,22].

To tackle these issues, Abbott and Crego conducted extensive anatomical investigations and made alterations to their original approach. Abbott endeavored to address the problem of soft tissue resistance by performing a thorough dissection of the fascia, periosteum, and interosseous membrane [5,22]. Initially, he separated all muscle origins on the proximal part of the tibia through subperiosteal dissection, with the actual lengthening procedure conducted in a subsequent surgery [5,22]. Additionally, he waited for up to 2 weeks after the osteotomy before commencing the lengthening process [5,22].

During the 1930s, Abbott and Crego's technique for limb lengthening underwent various modifications. In 1928, Carrell made the initial alteration to Abbott's method by adding a third pin in front of the tibial fragments to prevent their forward angulation caused by the tension in leg muscles [19,22]. However, this adjustment led to serious skin problems in some cases. In 1930, White incorporated Steinmann pins into an encircling plaster and used threaded rods for gradual distraction, a process taking 30 days for a 5 cm lengthening [13,23]. This innovation allowed patients to leave their beds.

In 1932, Dickson, Diveley [24], Haboush, and Finkelstein [24] substituted Kirschner wires for Steinmann pins, and Haboush and Finkelstein introduced a technique where they avoided dividing the periosteum during tibial osteotomy [24]. This change allowed the distal tibial fragment to glide within a periosteal sleeve, promoting faster callus formation and bone union [19].

In New York during the same decade, Bosworth worked on improving limb-lengthening techniques [25]. He coined the term "bone distraction" and stressed the importance of using a rigid frame [13]. While Bosworth still followed Abbott's method, he recommended delaying the lengthening process until ten days after osteotomy or until there were no signs of hematoma or infection [19].

In 1936, Edward L. Compere summarized the pros and cons of bone lengthening procedures [26]. He found that every surgeon attempting the operation faced complications, which could be categorized into three groups: overstretching, interference with blood supply to fragments, and insufficient fixation [19].

Post-World War II Renewed Interest

After World War II, there was renewed interest in leg lengthening. In 1950, Allan modified the Haboush and Finkelstein apparatus, using Kirschner wires for controlled progressive distraction. He advocated for an oblique osteotomy and minimizing damage to soft tissues [27]. Allan achieved bony union in all patients [13]. Others explored different fixation methods, such as McCarroll's slotted plate with traction and Bost and Larsen's intramedullary rod [19].

In Europe, surgeons like Anderson in Edinburgh adopted Abbott's technique in 1933 [13] and introduced percutaneous modifications in 1952 [19]. Anderson's method involved fibular osteotomy and tibial lengthening, but it was challenging and had complications. Coleman, Noonan, Gross, and Mitchell refined this technique by immediately fixing the fibula to the tibia and performing the tibial osteotomy in one stage [19]. Agerholm made the osteotomy zigzag to enhance stability [28], and Kawamura performed the osteotomy through the cortex to preserve nutrient vessels and endosteal tissue [29].

Wagner and Distraction Osteogenesis

Modern advancements in callus distraction for bone lengthening began in the early 1960s with Wagner's work [30]. Between 1970 and 1990, the Wagner approach to limb lengthening gained more popularity among pediatric orthopedic surgeons compared to the Anderson technique [31]. Wagner emphasized slow, gradual lengthening and developed a device that allowed 1.5 mm of lengthening per revolution, promoting daily progress while preserving limb function [19]. This method involves the use of a one-sided fixator that allows the patient to leave their bed, and it employs a three-stage plan to expedite the treatment process. Wagner's concept involves cutting the periosteum, fascia, and other restrictive tissues to minimize resistance. The lengthening is limited to a maximum of seven centimeters, and relatively rapid distraction (up to two millimeters per day) is applied, as tolerated by the awake patient. Once the intended amount of distraction is achieved, bone grafting is performed to fill the defect. The mid-diaphyseal osteotomy is executed using an oscillating saw, and a specially designed internal fixation plate replaces the external fixator once the lengthening goal is met [31]. The method did not provide significant benefits in terms of enabling the patient to mobilize early. It did not consider the soft tissues and the fundamental biological principles of distraction osteogenesis, and it required multiple significant surgical procedures. Despite these drawbacks and associated complications, Wagner's approach thrived in Germany and eventually made its way to the United States [5].

Ilizarov and Modern Limb Lengthening

While Wagner was refining his technique in Western countries, Ilizarov was working in Kurgan, Siberia, where he introduced a groundbreaking approach that successfully combined the surgical principles of limb lengthening with the biological processes of distraction histiogenesis [19]. In 1951, he initially applied this technique to treat a bone defect resulting from tuberculosis [32]. His innovation involved the development of a circular external skeletal fixation system, which utilized tensioned transfixion wires to secure the bone. These rings were interconnected by threaded rods, to stimulate and harness the body's natural tissue regeneration capabilities [5].

In 1952, Ilizarov introduced the modular ring fixator, which enabled precise and predictable results [8]. By 1954, he had used this technique to heal conditions like pseudarthroses and fibrous nonunions, employing a combination of local compression followed by distraction. He understood the beneficial effects of compression on bone healing and distraction on the formation of new tissue [5,33]. Following distraction, he once again utilized compression to convert the cartilaginous interface into new bone. In 1956, while correcting an ankylosed knee flexion deformity through an open osteotomy, distraction with an external fixator, and bone grafting, Ilizarov observed new bone formation within the distraction space [5,34].

In 1969, Ilizarov reported on a method of lengthening without the use of bone grafts. He noted that living tissue, when subjected to gradual and consistent traction, becomes metabolically activated in both the biosynthetic and proliferative pathways [37]. Ilizarov achieved this by applying pure distraction to a specialized corticotomy that preserved the medullary blood supply while only involving the osteotomy of the cortex. Using this technique, he successfully induced new bone formation at the site of lengthening [5].

Ilizarov's techniques gradually overcame the reservations associated with older procedures [32]. Initially, the technique was relatively unknown outside of Russia, while Wagner's technique was prevalent in German-speaking countries and later in the United States. However, concerns regarding the number of procedures required and high complication rates with the Wagner technique led to a shift in focus towards Ilizarov's method [5]. By 1983, over 15,000 patients had received treatment at his Institute, and approximately 9,000 patients were treated there annually, with over 300,000 individuals having undergone the treatment worldwide [32].

In 1994, the introduction of hexapod circular fixators, particularly the well-known Taylor Spatial frame by Charles Taylor and his brother Harold, represents the most significant development in the evolution of Ilizarov's original apparatus up to now [35]. The Taylor Spatial frame consisted of an external fixator, equipped with adjustable struts and accompanying computer software, that drew inspiration from Stewart's "platform with 6 degrees of freedom" concept, enabling the concurrent correction of intricate deformities across multiple planes [36].

To expedite the external fixation period, alternative approaches were devised. These methods included lengthening with a small-diameter nail and lengthening followed by nailing or plating [37]. Initially introduced by Bost and Larsen in 1956, the lengthening over nails method gained popularity through its adoption by Paley et al [38]. They managed to reduce the time spent in the external fixator by employing the lengthening-over-nail method, which demonstrated a relatively moderate rate of complications [37]. The procedure involves an osteotomy during the initial surgery, the insertion of an intramedullary nail, and proximal locking, followed by the application of an external fixator. Once the predetermined lengthening goal for the tibia is achieved, interlocking screws are inserted into the nail, and the external fixator was removed [39]. The intramedullary nail plays a crucial role in stabilizing the regenerated bone during the consolidation phase, safeguarding it from bending and fractures. This technique effectively prevents axial deviations of the lengthened skeletal segment, fractures of the regenerated bone after external fixator removal, and joint stiffness [40].

Internal Lengthening Devices

In 1983, Alexander Bliskunov pioneered the development of the first internal lengthening device [41]. This implant comprises a telescopic nail elongated using an internal ratchet system. To activate the ratchet, Bliskunov connects one end of the device, via a universal joint, to the outer wall of the iliac crest. By rotating the hip internally and externally, the nail extends [42]. Subsequent refinements were made by Götz and Schellmann with the introduction of a hydraulic distractor nail [41,43], while Baumann and Harms later introduced an intramedullary extension nail [41,44]. These advancements paved the way for the creation of various other intramedullary lengthening devices.

In 1989, Betz and Baumgart introduced a motorized lengthening device that didn't rely on a telescopic mechanism [45]. The nail operates using an internal motor connected to a subcutaneously implanted antenna activated through external radiofrequency stimulation [41]. In 1988, Grammont and Guichet developed the Albizzia telescopic nail, consisting of two telescoping tubes: an outer threaded tube and an inner rod connected by a double-opposed ratchet mechanism [46]. By rotating the inner tube by 20 degrees, the ratchet mechanism unscrews, extending the nail by 1/15 of a millimeter. The nail resets when rotated back to its resting position [46]. Guichet modified the Albizzia nail, naming it the G-Nail, while Betz made further modifications to the ratchet mechanism, interlocking system, dimensions, and design, resulting in the Betzbone nail and a change in the orientation of the locking holes [41].

In 2001, the intramedullary skeletal kinetic distractor (ISKD) was introduced, employing a similar lengthening principle involving the rotation of a ratchet mechanism [47]. Unlike the Albizzia nail, only 3 to 9 degrees of rotation were required for lengthening [41,48]. The primary issue associated with the ISKD was the occasional excessively rapid lengthening once postoperative pain subsides. This accelerated lengthening led to suboptimal regenerative bone formation and symptoms of neurovascular complications, characterized by tingling sensations and later progressing to numbness [42]. The first motorized intramedullary lengthening nail, known as the Fitbone was created by Rainer Baumgart in Germany in 1997 [42], it featured an electric motor without a built-in battery. Instead, it relied on electricity transmitted through an induction coil positioned beneath the skin [42]. Another induction coil, placed externally on the body near the internal coil, transmitted power to the implant. This technology has been effectively utilized worldwide but has not received approval from the FDA for use in the United States [42]. In 2009, Pool and Walker developed the Precice magnetically driven, titanium intramedullary lengthening nail, which is activated by an external magnetic field generator causing a magnet inside the nail to rotate and facilitate lengthening [41,49]. The initial achievements of the Precice intramedullary lengthening nail, particularly its positive reception among patients who had previously undergone limb lengthening using external skeletal fixators, prompted surgeons to explore methods for completely removing external fixators in complex limb reconstruction procedures [50].

Both the Precice nail and its predecessor, the ISKD, were made of titanium alloy and required weight-bearing restrictions [51]. In contrast, the Albizzia nail, which predates both, is made of cobalt chrome and allows full weight-bearing as tolerated. Similarly, the Fitbone nail, a stainless-steel implantable lengthening nail, also permits full weight-bearing [51].

In April 2018, the Precice Stryde nail received approval from the USA Food and Drug Administration and obtained European CE certification in February 2019 [52]. The primary difference, when compared to previous implants like the Precice, the ISKD, or the Fitbone nail, is the change in implant design and material. The Stryde nail is made of Biodur stainless steel and features a modified distraction mechanism that enables full weight-bearing during lengthening [53]. However, there is a lack of comprehensive studies analyzing the use of the Stryde nail in large groups of patients [52].

In January 2021, the manufacturer withdrew the Stryde system from the market and issued a field safety notice due to concerns about biocompatibility and implant-related complications. Regulatory agencies in Europe and the UK raised safety concerns related to this development [54,55].

Latest Advances in Bone Lengthening and Distraction Osteogenesis

There are situations where intramedullary lengthening nails are not appropriate, especially in small or skeletally immature patients [56]. To address this challenge creatively and avoid using external fixators in such cases, a novel concept emerged involving the unconventional use of intramedullary nails placed "extramedullary" [56]. In 2020, two reports discussed an "off-label" approach where lengthening nails were positioned outside the medullary canal for femoral and tibial lengthening in a forward direction [56]. Dahl noticed a potential issue of secondary deformity with this method [57]. To address this problem, Shannon introduced the use of an intramedullary rod for additional support [58]. In 2021, Iobst and Bafor introduced a technique for femur lengthening in skeletally immature patients using an extramedullary magnetic lengthening nail inserted in a reverse direction [59]. This nail orientation capitalized on its proximal bend to achieve a precise anatomical fit, eliminating the need for additional fixation [60].

Numerous biophysical and biological treatments have been explored to enhance bone formation during distraction osteogenesis in both animals and humans [61]. These approaches have included methods like electronic stimulation, exposure to hyperbaric oxygen, the application of low-intensity pulsed ultrasound, systemic administration of recombinant growth hormone, and procedures involving the transplantation of fresh bone marrow cells or recombinant human bone morphogenetic proteins [62].

Prior studies demonstrated that the combination of BMC (bone marrow cells) and PRP (platelet-rich plasma) accelerated bone healing and remodeling by stimulating angiogenesis. In 2007, Kitoh et al. were the first to report successful outcomes in patients undergoing femoral and tibial lengthening using this approach, reducing treatment duration and complications by accelerating new bone formation in distraction osteogenesis [62].

In 2011, Dudda et al. found that low-intensity pulsed ultrasound (LIPUS) during callus distraction was a beneficial adjunctive treatment during distraction osteogenesis, positively impacting healing time without adverse effects [63].

Additionally, various molecules, including bone morphogenetic protein (BMP), fibroblast growth factor-2, parathyroid hormone, and sclerostin antibody, have been investigated to enhance bone regeneration in animal models of distraction osteogenesis [61]. While animal experiments consistently support the positive effects of these treatments on bone regeneration, their clinical significance remains uncertain.

Most recently, in 2021, Yukata et al. [61] used a mouse tibial lengthening model to demonstrate that osteoactivin acts as an inhibitor of callus resorption during the consolidation phase of distraction osteogenesis. As a result, osteoactivin could potentially be a valuable clinical tool to maintain bone strength by preventing excessive callus remodeling during distraction osteogenesis [60].

In a comprehensive two-part review and meta-analysis conducted by D'Andrea et al. in 2021, the modulation of longitudinal bone growth and growth plate activity, at both macro and micro scales, comes into focus, shedding light on the potential directions for distraction osteogenesis [60, 64, 65]. At the macro scale, it becomes evident that changes in longitudinal bone growth resulting from mechanical loading hinge on various factors, including load magnitude, anatomical location, and species [60]. On a micro-scale perspective, an essential stride toward achieving progressively less invasive corrections of skeletal deformities lies in our understanding of how mechanical loading triggers alterations in gene and protein expressions. This knowledge could pave the way for innovative methods extending beyond mechanical modulation [60].

Ethical Considerations and Guidelines for Cosmetic Limb Lengthening

The success and application of Ilizarov's limb lengthening technique have expanded its use beyond pathological conditions such as achondroplasia, war injuries, congenital and acquired limb length discrepancies, and bone defects. Now, it includes the cosmetic enhancement of height as well [66]. A growing number of individuals dissatisfied with their height aspire to increase it by a few inches [67]. This, coupled with the significant emotional and social consequences short stature can have on an individual, has led to a rising trend of cosmetic limb lengthening procedures [68].

This increasing trend is influenced by commonly held beliefs about the social challenges linked to shorter stature and the potential benefits being taller could have such as heightened self-confidence, improved job prospects, enhanced sports involvement, and better interpersonal connections [66,69]. In contrast to cases involving limb length discrepancy and bone defects, where the extent of lengthening is determined by the pathology, cosmetic lengthening requires a careful balance between the "safety factor" and the patient's "expectations" for optimal results [70]. Excessive lengthening, as observed in pathological conditions, consistently raises the risk of complications and compromise of function.

Despite existing reports on the outcomes of the Ilizarov technique for cosmetic purposes, there is a lack of guidelines that specify the safe limits for the extent of lengthening [66]. The literature also lacks comprehensive information regarding the risks, long-term consequences, indications, and contraindications associated with the use of the Ilizarov method for height augmentation, especially when undertaken solely for aesthetic reasons. Given that individuals seeking cosmetic limb lengthening are typically physically healthy, it is of paramount importance to ensure that the pursuit of cosmetic enhancements does not compromise functional aspects [71].

Due to the limited research on distraction osteogenesis for cosmetic purposes, Novikov et al. conducted a comprehensive review of a patient cohort that underwent cosmetic lengthening of the lower extremities. The study addressed challenges related to soft tissue, complications associated with bones, and both functional and subjective clinical outcomes [68]. While complications were anticipated, most were effectively managed without permanent consequences or disability. To establish the safety and efficacy of this procedure, future studies with more robust methodologies will be essential.

Building on this foundation, Novikov investigated safe limits for cosmetic tibial lengthening and explored how the patient's age and the extent of lengthening influence osteogenesis and complications [71]. The findings indicated that older age is linked to a prolonged period of external fixation, and a greater extent of lengthening introduces more challenges and complications. Therefore, careful consideration is crucial when contemplating cosmetic tibial lengthening beyond the threshold of 16%.

Another study by Elbatrawy et al. [67] examined the long-term results of patients undergoing cosmetic limb lengthening using Ilizarov's ring external fixator with a maximum stability technique. The study affirms the safety of the Ilizarov device for limb lengthening in individuals of short stature, specifically when employing the authors' technique for achieving maximum frame stability. Postoperative psychological assessments revealed enhanced self-confidence and improved psychological well-being. However, some patients encountered psychological challenges during the procedure that were not identified preoperatively, highlighting the need for thorough psychological evaluation before initiating cosmetic lengthening surgery.

For individuals diagnosed with body dysmorphic disorder or dysmorphophobia, satisfaction post-limb lengthening may not be predictable [72]. These patients seek cosmetic surgery to alter their perceived abnormal appearance. Hence, a mandatory preoperative psychological assessment becomes crucial to rule out psychiatric disorders and understand the patient's personality and motivations [73].

In addition to psychological evaluation, thorough preoperative counseling with the treating surgeon is crucial. This counseling aims to assess the surgery's necessity, provide a comprehensive understanding of the treatment and potential complications, and explore non-surgical alternatives when possible [73].

The transition from external fixators to lengthening nails in limb elongation mechanics hasn't resolved numerous complications associated with the process [74]. Paley pioneered the use of the Precice intramedullary lengthening nail for cosmetic stature surgery. In a 2015 assessment of the device's market potential [49], Paley documented 15 patients undergoing stature surgery for achondroplasia or cosmetic reasons. Three patients underwent bone grafting due to failed regeneration, all congenital cases. Three nails fractured and needed replacement. Seven nails in six patients ceased lengthening during the distraction, two attributed to operator error. In five other cases, the internal mechanism failed, possibly due to stiffening regeneration or robust thigh muscles. Many of Paley's patients initially received the first-generation Precice nail, which exhibited weak spots in its welds, leading to implant breakage under stress. The subsequent Precice 2 (P2) nail has successfully addressed this issue, and the company has continuously enhanced the internal mechanism, resulting in rare occurrences of motor failures.

Guidelines for cosmetic limb lengthening are essential due to the absence of clear signals and restrictions regarding the appropriate timing for offering this surgery to individuals of shorter stature. The ethical debates surrounding this procedure further underscore the necessity for such guidelines [75]. Despite being viewed as unnecessary and risky by some, there is a significant and increasing global desire for it. Those advocating for this surgery argue that if individuals can undergo procedures like breast augmentation or gender reassignment, why should limb lengthening be excluded [75]?

At the 2016 joint meeting of the Association for the Study and Application of the Method of Ilizarov-Bone Reconstruction (ASAMI-BR) and the International Limb Lengthening and Reconstruction Society (ILLRS) in Brisbane, Patel and colleagues deliberated on guidelines and standards for cosmetic limb lengthening. They aimed to empower the constituent national bodies within ASAMI and ILLRS to advocate their respective governments and medical regulators for the enforcement of these guidelines.

These are the proposed guidelines for ethical cosmetic limb lengthening surgery [75]:

1. Surgery must only be performed by experienced fellowship-trained limb reconstruction surgeons.

2. Surgery must only be performed in major hospitals with backup facilities.
3. While initial consultations may be through remote means such as the Internet, there must be at least one in-person consultation before surgery. There must be a detailed informed consent procedure.
4. There must be a psychological assessment of the patient and ongoing pastoral care of the patient.
5. There must be a minimum cooling-off period to allow the patient to call off the surgery, without any financial or other penalty.
6. There must be clear avenues for complaint for the patient, including the right to redress in case of unacceptable outcomes and complications.
7. The surgeon must have a commitment to manage the patients till the completion of their treatment, including rehabilitation and management of their complications.
8. There must be no financial exploitation of patients. This includes a prohibition on nonrefundable deposits, and a commitment to manage complications for little or no extra cost, irrespective of the patient's ability to pay.
9. National bodies have a duty to report or reprimand underperforming or exploitative colleagues, and those that indulge in unethical practice.

Discussion:

The field of limb lengthening has undergone remarkable progress in recent years, driven by the integration of cutting-edge devices and technologies rooted in fundamental biomedical principles. Despite its historical origins, limb lengthening surgery remains a relatively young discipline in modern medicine, evolving from addressing wartime injuries and congenital deformities to encompassing aesthetic considerations. From Ilizarov's pioneering contributions to the latest advancements, limb lengthening represents a fascinating journey in orthopedics.

Ilizarov's circular external skeletal fixation system laid the foundation for modern limb lengthening, overcoming challenges associated with older procedures and facilitating widespread adoption worldwide. Subsequent developments, such as hexapod circular fixators and intramedullary devices, marked milestones in precision enhancement and external fixation period reduction. Internal lengthening devices, including motorized and magnetically driven nails, broadened options for patients, offering alternatives to traditional external fixators. However, the withdrawal of the Stryde system in 2021 underscored the need for ongoing scrutiny and comprehensive studies to assess safety and efficacy.

As limb lengthening applications extend beyond pathology to cosmetic enhancements, ethical considerations become crucial. The surge in cosmetic procedures necessitates careful guidelines to ensure patient safety and ethical practice. In the realm of cosmetic limb lengthening, distinctive challenges arise, requiring a delicate balance between patient expectations and safety. Limited research underscores the need for robust methodologies and comprehensive studies to establish safe limits and outcomes. Psychological evaluations, preoperative counseling, and awareness of potential complications are crucial for the well-being of individuals seeking cosmetic enhancements.

Looking ahead, advancements in limb lengthening may continue to push innovation boundaries, focusing on improving patient outcomes, reducing complications, and addressing ethical considerations. Interdisciplinary collaboration among surgeons, researchers, and regulatory bodies remains pivotal in guiding limb-lengthening evolution and ensuring responsible application in diverse clinical scenarios. However, this shift necessitates careful consideration of ethical principles and psychological factors. As limb lengthening for aesthetic purposes becomes more common, ethical considerations come to the forefront. Physicians must weigh the ethical implications, especially when there is no medical necessity [76]. Clear guidelines and ethical frameworks should be in place to ensure patients fully understand risks and benefits, making informed decisions. Despite advancements, challenges like soft tissue complications, joint contractures, and nerve damage persist [36]. Thus, prioritizing patient safety over additional length is paramount, requiring thorough preoperative evaluation, meticulous surgical planning, and vigilant postoperative care to minimize risks and ensure optimal outcomes.

Conclusion:

Exploring the historical trajectory of limb lengthening in science and medicine provides a valuable context for understanding and appreciating the latest advancements in cosmetic limb lengthening procedures. The evolution of limb-lengthening techniques has not only contributed to the treatment of various medical conditions but has also gained traction in the realm of cosmetic surgery, catering to individuals seeking aesthetic improvements. These strides have not only broadened the possibilities of limb lengthening but have also resulted in enhanced patient outcomes and a reduction in complications. Though complications have been reduced, they have not been eliminated. As the applications of limb lengthening now extend beyond addressing pathological conditions to encompass cosmetic enhancements, the importance of ethical considerations has become increasingly pronounced. The rise in cosmetic procedures underscores the necessity for meticulous guidelines to safeguard patient safety and uphold ethical standards. It is imperative to establish clear guidelines and ethical frameworks to ensure that patients are well-informed about the associated risks and benefits. This will empower them to make informed decisions regarding limb-lengthening procedures, fostering a balance between technological advancements and ethical medical practice.

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