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Radial Longitudinal Deficiency: A Contemporary Clinical Review From Deformity to Function

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Abstract

Radial longitudinal deficiency (RLD), historically known as radial club hand, is a congenital malformation of the upper limb in which the structures along the preaxial (radial) axis - the thumb, radius, radial carpal bones, and radial-sided soft tissues - are hypoplastic or absent. It occurs across a broad spectrum, from isolated thumb hypoplasia to complete radial aplasia, which may be accompanied by radial deviation of the wrist, forearm shortening, and impaired hand function. Its clinical importance extends well beyond the visible limb difference: a substantial proportion of affected children have systemic anomalies, and RLD can be the presenting sign of conditions with major health implications, including Fanconi anemia, Holt-Oram syndrome, thrombocytopenia-absent radius syndrome, VACTERL association, and Baller-Gerold syndrome. Because these disorders carry independent hematologic, cardiac, renal, and other risks, early recognition and systemic evaluation are integral to the initial assessment rather than secondary to it. Classification systems that describe both the radial deficiency and the associated thumb hypoplasia help stratify severity and guide management, while evaluation is directed at both the limb and possible systemic involvement. Management is individualized and multidisciplinary, spanning hand surgery, genetics, occupational therapy, and psychosocial support, and combines nonoperative measures with surgical reconstruction in more severe cases. The evidence base remains limited, consisting largely of small, heterogeneous, retrospective series with variable outcome measures and short follow-up; however, important questions about optimal technique and timing remain unresolved. Optimal care therefore depends on individualized, multidisciplinary treatment planning that prioritizes long-term function, growth preservation, and the psychosocial well-being of patients and their families.

Categories: Plastic Surgery, Physical Medicine & Rehabilitation, Orthopedics
Keywords: centralization, congenital upper limb anomaly, fanconi anemia, functional outcomes, holt-oram syndrome, pollicization, radial club hand, radialization, radial longitudinal deficiency, thumb hypoplasia

Introduction And Background

Radial longitudinal deficiency (RLD), widely recognized by the historical term *radial club hand*, is a congenital malformation of the upper extremity characterized by deficiency along the radial (preaxial) axis of the forearm and hand. The term *radial club hand* describes the characteristic appearance of radial deviation of the hand at the distal forearm, which resembles a golf club, and remains in common clinical use [1]. RLD encompasses a spectrum of severity that ranges from mild hypoplasia of the thumb or distal radius to complete absence of the radius with severe radial wrist deviation, carpal abnormalities, and thumb aplasia [1]. In all forms, deficiency of the radial column results in varying degrees of structural and functional impairment in the wrist, hand, and thumb.

The clinical significance of RLD extends beyond its musculoskeletal presentation. A substantial proportion of affected individuals have associated systemic anomalies, and RLD may represent the presenting feature of conditions requiring urgent evaluation, including Fanconi anemia, which carries a risk of hematologic malignancy, and Holt-Oram syndrome, which is associated with structural cardiac defects [2,3]. Recognition of these associations and completion of appropriate systemic evaluation are therefore essential components of the initial evaluation, rather than secondary concerns following orthopedic assessment.

A nationwide Finnish case-control study reported a birth prevalence of radial ray deficiency of approximately 1.2 per 10,000 births, toward the upper end of previously published estimates of 0.3-1.6 per 10,000 live births [4]. RLD is the most common congenital longitudinal deficiency of the upper limb [3], and in a Finnish population-based series, it was the most frequent upper limb deficiency of any type [5].

Management of RLD should be individualized to the patient and family [6] and is ideally delivered by a multidisciplinary team including pediatric hand surgeons, geneticists, occupational therapists, and psychosocial support providers. Surgical techniques have evolved substantially over the past several decades, yet long-term comparative outcome data remain limited by the rarity of the condition and the heterogeneity

of available cohorts.

The aim of this narrative review is to provide an overview of RLD, including its embryology, genetic and syndromic associations, classification, clinical presentation, diagnostic evaluation, and management, with an emphasis on clinically relevant decision-making and areas where evidence remains limited.

Review

Methodology

This is a narrative review and was not conducted as a systematic review. PubMed was the primary bibliographic database, supplemented by Google Scholar, and GeneReviews was consulted for syndrome-specific clinical and genetic information. The review emphasized peer-reviewed publications from 1990 onward, particularly those published from 2015 onward; earlier foundational reports, including the original descriptions of classification systems, were also reviewed. Sources were selected for their relevance to the epidemiology, embryology, genetics, classification, clinical presentation, diagnosis, management, and outcomes of RLD. Where RLD-specific evidence was limited, studies of related congenital upper limb differences and pediatric rehabilitation were included, and the populations studied are specified in the text. Consistent with the narrative design, no formal risk-of-bias assessment or quantitative pooling (meta-analysis) was performed.

Epidemiology

Incidence and Prevalence

Population-based studies from Finland have identified radial ray deficiency as the most common congenital deficiency of the upper limb. In a Finnish population-based series of 419 upper limb deficiencies among 753,342 births, radial ray deficiency was the single most frequent subtype (138 cases), exceeding undergrowth, constriction band syndrome, central ray deficiency, and ulnar ray deficiency [5]. Reported prevalence varies with the study period, case definition, and whether milder phenotypes, such as isolated thumb hypoplasia, are captured [4,5]. Because the deformity is typically apparent at birth, prevalence estimates largely reflect incidence at delivery.

Sex, Laterality, and Geographic Patterns

A modest male predominance has been reported. In the Finnish population-based series, 58% of the 138 children with radial ray deficiency were male [5], and in a U.S. series of 164 patients with RLD, 90 were boys and 74 were girls [7]. In the Finnish case-control study, no significant risk factors were identified for nonsyndromic cases; within the syndromic subgroup, male sex was associated with higher odds of radial aplasia (adjusted odds ratio, 1.96; 95% CI, 1.18-3.25) [4]. In a direct comparison of Japanese and U.S. cohorts (194 Japanese patients with 290 involved extremities and 107 U.S. patients), Japanese patients showed higher rates of associated syndromes and radial polydactyly, whereas U.S. patients showed greater RLD severity and higher rates of bilateral involvement, suggesting differences in phenotype expression and ascertainment rather than definitive differences in baseline risk [8].

Registry-Based Data

Across population-based studies from Finland, Australia, Japan, and the United States, baseline prevalence estimates are broadly similar when similar case definitions are applied. Apparent discrepancies frequently reflect variation in classification criteria, the inclusion of stillbirths or terminations, and the ascertainment of milder phenotypes [2,4,5,8-11].

The Congenital Upper Limb Differences (CoULD) registry, which uses the Oberg-Manske-Tonkin (OMT) classification and captures both surgically and nonsurgically managed cases, identifies a higher relative frequency of RLD and thumb hypoplasia compared with birth registries or single-center cohorts [12]. The severity of radial deficiency correlates with the severity of thumb hypoplasia, an association that is particularly relevant in syndromic patients (e.g., VACTERL, Holt-Oram syndrome, TAR syndrome, and Fanconi anemia) [3]. Population-based registries such as the New York Congenital Malformations Registry and the Australian Hand Difference Register (AHDR) report lower frequencies of syndromic cases and somewhat different phenotypic distributions, which are primarily attributable to differences in inclusion criteria, data collection methods, and case ascertainment [13,14].

Embryology and pathogenesis

Upper limb development begins during the fourth week after fertilization with the outgrowth of the limb bud from the lateral plate mesoderm. Patterning of the limb occurs along three axes: proximal-distal, dorsal-ventral, and anterior-posterior (radial-ulnar) [15,16]. The anterior (preaxial, radial) side of the limb bud is established by gradients of signaling molecules that govern mesenchymal cell proliferation and differentiation. Disruption of these gradients during the period of rapid limb development, which begins

when the limb bud appears 26-28 days after fertilization and continues over approximately the following 4 weeks, can result in hypoplasia or absence of the radius, thumb, and associated radial carpal elements while leaving ulnar structures relatively preserved [15,16].

Several signaling pathways have been implicated in RLD pathogenesis. Sonic hedgehog (SHH), secreted from the zone of polarizing activity at the posterior limb bud, establishes radial-ulnar identity; ectopic or abnormal SHH signaling can produce both preaxial polydactyly and radial deficiencies, supporting a shared developmental origin for these anomalies [17,18]. The canonical Wnt pathway, including genes such as RAC1, is essential for limb outgrowth and patterning; deletions affecting components of this pathway have been associated with truncated limb defects and radial ray deficiencies [19,20]. Bone morphogenetic protein (BMP) signaling regulates digit and joint development, and dysregulation of this pathway can contribute to skeletal dysplasia [18,21]. Fibroblast growth factor 8 (FGF8), produced by the apical ectodermal ridge, contributes to proximal-distal limb outgrowth; disruption of the ΔNp63α-DLX5/FGF8 regulatory axis has been implicated experimentally in malformations of the central rays of the hands and feet [22].

The timing of embryological disruption explains why RLD can affect multiple structures along the radial axis, including the thumb, radius, radial carpal bones, and radial forearm musculature, while leaving more ulnar structures relatively intact [15,16]. In Adams-Oliver syndrome, a distinct mechanism of vascular disruption during embryogenesis produces terminal transverse limb defects and aplasia cutis congenita (scalp defects). Causative mutations have been identified in genes involved in vascular development and Notch signaling, including NOTCH1, DLL4, RBPJ, ARHGAP31, DOCK6, and EOGT [23,24].

Genetic and syndromic associations

Overview

RLD occurs in both isolated (nonsyndromic) and syndromic forms. Approximately half of cases occur as components of recognized syndromes with Mendelian inheritance [2,10]. The remainder are sporadic or associated with nongenetic risk factors, although many sporadic cases likely reflect de novo mutations or polygenic contributions that remain incompletely characterized [2,19]. Nonsyndromic cases demonstrate high inter- and intrafamilial variability, and many lack a genetic explanation despite comprehensive testing [2]. Genetic research has identified microdeletions and duplications across multiple loci in some patients, which may reflect the overlapping developmental pathways involved in radial ray formation [19]. Distinguishing between isolated and syndromic RLD is a clinical priority, as syndromic cases carry independent systemic implications that alter surveillance requirements, perioperative management, and long-term prognosis. Maternal and environmental risk factors have been identified predominantly among syndromic cases. In a Finnish population-based case-control study, advanced maternal age (adjusted odds ratio, 2.45; 95% CI, 1.37-4.36), multiple pregnancy (adjusted odds ratio, 2.97; 95% CI, 1.16-7.62), and valproic acid exposure ($P = 0.002$) were associated with radial aplasia in the syndromic subgroup, whereas no significant risk factors were found for nonsyndromic cases [4]. Teratogenic exposures, including antiepileptic medications, should therefore be specifically elicited in the clinical history [2,4].

Holt-Oram Syndrome

Holt-Oram syndrome is caused by autosomal dominant variants in TBX5, a T-box transcription factor gene essential for cardiac and upper limb development [2]. Affected individuals present with upper limb malformations, ranging from thumb hypoplasia to radial aplasia, and congenital cardiac defects, most commonly atrial or ventricular septal defects. Cardiac arrhythmias may occur independently of structural cardiac defects. Patients with suspected Holt-Oram syndrome may require echocardiographic evaluation before surgical planning, as unrecognized cardiac disease increases perioperative anesthetic risk [2,6].

Fanconi Anemia

Fanconi anemia is caused by biallelic pathogenic variants in genes encoding proteins of the Fanconi anemia DNA repair pathway (FANC genes), impairing the cellular response to DNA interstrand crosslinks [2,3]. Affected patients present with congenital anomalies, including thumb and radial ray defects, and are at substantially increased risk of progressive bone marrow failure and hematologic malignancies, particularly acute myeloid leukemia. The prevalence of Fanconi anemia among children presenting with congenital thumb anomalies is low. In a single-institution series, 543 children presented with congenital thumb anomalies, and 81 underwent diepoxybutane testing; 6 were confirmed to have Fanconi anemia, representing approximately 7% of those tested and roughly 1% of all children who presented with thumb anomalies [25]. Nonetheless, identification is critical, including in seemingly isolated presentations such as unilateral thumb polydactyly, because affected patients require disease-specific hematologic surveillance and management [25,26].

Diepoxybutane (DEB) chromosome breakage testing is a standard diagnostic test for Fanconi anemia. DEB testing detects characteristic chromosomal hypersensitivity to DNA crosslinking agents, distinguishing Fanconi anemia from other causes of bone marrow failure or radial ray deficiency [3]. Preoperative DEB

testing should be considered in any patient with radial ray anomalies and clinical features suggestive of Fanconi anemia, given the perioperative implications of thrombocytopenia, neutropenia, or occult hematologic malignancy. When bone marrow abnormalities are identified preoperatively, surgical intervention for RLD can proceed with hematologic optimization, heightened infection precautions, and close monitoring for bleeding and wound-healing complications [3,6].

Thrombocytopenia-Absent Radius Syndrome

Thrombocytopenia-absent radius (TAR) syndrome is characterized by bilateral radial aplasia in the presence of a normal or near-normal thumb - a critical distinguishing feature that differentiates TAR syndrome from other causes of RLD - combined with thrombocytopenia [27]. Causative variants most commonly involve compound heterozygosity for a rare null allele and a common low-frequency single-nucleotide polymorphism in RBM8A, which encodes the Y14 component of the exon junction complex [27]. Thrombocytopenia in TAR syndrome is typically most severe in infancy and tends to improve with age. Cardiac anomalies may also be present and require evaluation prior to operative intervention [27].

VACTERL Association

VACTERL association encompasses the nonrandom co-occurrence of vertebral defects, anal atresia, cardiac malformations, tracheoesophageal fistula with esophageal atresia, renal anomalies, and limb defects [2]. Radial ray deficiency is the most common limb abnormality identified in VACTERL; however, isolated radial defects do not constitute a VACTERL diagnosis in the absence of additional anomalies involving at least two other organ systems. VACTERL is a clinical diagnosis, and no single causative gene has been identified. A thorough systemic evaluation is warranted in any patient with RLD and additional organ system involvement.

Baller-Gerold Syndrome and Additional Associations

Baller-Gerold syndrome is an autosomal recessive condition caused by mutations in RECQL4, a RecQ helicase gene involved in DNA replication and repair, and is characterized by craniosynostosis together with radial ray anomalies [2]. SALL4-related disorders, including Duane-radial ray (Okihiro) syndrome, are associated with radial ray defects alongside ocular motility and renal anomalies [2]. Recognition of these associations is clinically important, as each carries distinct surveillance requirements and perioperative considerations.

Prenatal Genetic Diagnosis

Genome and exome sequencing of fetal DNA, obtained via chorionic villus sampling or amniocentesis, can identify causative variants when a fetal skeletal abnormality is detected. In a cohort of 32 fetuses with suspected genetic skeletal disorders, genome sequencing achieved a molecular diagnosis in 72% (23 of 32); because this cohort was not specific to RLD, this yield should not be extrapolated directly to isolated radial ray anomalies [28]. The Society for Maternal-Fetal Medicine recommends offering genetic counseling and diagnostic genetic testing when a radial ray malformation is identified on prenatal ultrasound, particularly when bilateral involvement or associated anomalies are present [29]. Accurate molecular diagnosis enables syndrome-specific surveillance, informs recurrence risk counseling, and may identify comorbidities with direct perioperative relevance [2,3].

Gene editing in utero for the treatment of RLD is not currently available in clinical practice. Proof-of-concept studies in animal models have demonstrated the technical feasibility of in utero gene modification for monogenic disorders, but clinical translation remains confined to preclinical research [30-33]. The barriers to application in RLD are substantial: the condition is genetically heterogeneous and frequently syndromic, effective postnatal treatments exist, and the ethical rationale for fetal intervention has not been established at this stage of technological development [30]. Additional concerns include off-target genomic effects, long-term safety uncertainty in a developing fetus, complexities of prenatal informed consent, and the potential for inequitable access to experimental interventions [31-33].

Classification systems

Historical Classification

The Swanson classification, which was endorsed for international use in the 1970s and adopted by the International Federation of Societies for Surgery of the Hand (IFSSH), grouped congenital upper limb anomalies into seven categories (e.g., failure of formation, failure of differentiation, and duplication) according to the parts primarily affected [34]. While clinically familiar to a generation of hand surgeons, the Swanson system could not readily incorporate later advances in developmental biology and genetic etiology, limiting its utility for guiding research and standardizing communication across institutions [35-37].

OMT Classification

The OMT classification represents the current standard for classifying congenital upper limb anomalies and has been adopted by the IFSSH [35,38]. Building on the developmental biology framework articulated by Manske and Oberg, the system distinguishes malformations (resulting from abnormal embryological formation), deformations (resulting from mechanical forces on otherwise normal structures), and dysplasias (resulting from abnormal cellular organization), while also subcategorizing malformations by the axis of development primarily affected (proximal-distal, radial-ulnar, or dorsal-ventral) and by whether the entire limb or only the hand plate is involved [35,36,39]. By integrating phenotypic presentation with developmental biology, the OMT system was designed to improve diagnostic consistency and standardize communication among clinicians, researchers, and registry platforms [35,36].

Bayne-Klug Classification

The Bayne-Klug classification, described by Bayne and Klug in their long-term review of surgically treated radial deficiencies, remains the most widely used system in clinical practice for grading the radiographic severity of RLD [40]. It defines four types based on radiographic findings: type I (short distal radial epiphysis; radius present but distally hypoplastic), type II (hypoplastic radius with abnormal growth plates at both ends), type III (partial absence of the radius, typically the distal portion), and type IV (complete absence of the radius) [40]. This classification directly informs surgical planning and is widely applied in published surgical outcome studies [3]. Types III and IV represent the most severe deformities and are most commonly the focus of centralization, radialization, and reconstructive procedures.

Blauth Classification for Thumb Hypoplasia

Thumb hypoplasia is a frequent and clinically critical component of RLD that requires independent classification. Blauth originally described five grades of thumb hypoplasia [41]; the modified Blauth classification summarized here incorporates the later subdivision of type III into IIIA and IIIB by Manske and colleagues [42-44]. Type I denotes minor generalized hypoplasia with all elements present, and type II adds thenar muscle hypoplasia with ulnar collateral ligament instability of the metacarpophalangeal joint. Type III involves intrinsic muscle deficiency with extrinsic tendon anomalies and is subdivided into IIIA, with a stable carpometacarpal (CMC) joint, and IIIB, with a deficient or unstable CMC joint. Type IV is a floating thumb (pouce flottant), attached only by skin and a neurovascular pedicle without functional skeletal continuity, and type V is complete thumb aplasia. Types I, II, and IIIA are generally candidates for thumb reconstruction and augmentation, whereas types IIIB, IV, and V are typically managed with pollicization of the index finger; in an international survey of pediatric hand surgeons, 94% and 100% of respondents favored pollicization for Blauth type IIIB and type IV thumbs, respectively [45]. Thumb function represents one of the most important determinants of upper extremity functional outcome and must be assessed independently of wrist and forearm deformities when planning surgical intervention.

Limitations of Current Classifications

The OMT system, while preferred for standardization, has been critiqued for practical challenges in classifying complex or phenotypically overlapping presentations and for its incomplete treatment of etiology in nonsyndromic cases [46]. The Bayne-Klug classification is practical for surgical decision-making but does not address associated anomalies or underlying etiology [3]. Neither system is fully predictive of functional outcomes, and further refinement is anticipated as our understanding of genotype-phenotype relationships evolves [37,46].

Clinical presentation

Spectrum of Deformity

RLD presents across a broad anatomic spectrum, reflecting the range of radial-sided deficiency, from mild thumb hypoplasia to complete radial aplasia with severe wrist deviation. When present as an isolated finding, RLD is confined to the musculoskeletal system, with skeletal, muscular, and neurovascular anomalies along the radial axis. When associated with a syndrome, additional organ systems may be involved, depending on the underlying condition [1,2]. A substantial proportion of patients with RLD have associated anomalies affecting other organ systems, most commonly the cardiac, genitourinary, and hematopoietic systems, and the likelihood of associated conditions increases with the severity of the radial deficiency [7].

Musculoskeletal Features and Functional Limitations

The characteristic musculoskeletal presentation includes radial deviation of the hand and wrist, forearm shortening and bowing due to differential growth in the absence of a supporting radius, and a spectrum of thumb abnormalities ranging from hypoplasia to complete aplasia. Carpal abnormalities, including the absence of radial carpal bones such as the scaphoid, trapezium, and trapezoid, are common and contribute to wrist instability and deviation [1]. Elbow motion may be limited, particularly in cases with associated elbow stiffness or humeroradial joint abnormalities [47]. Radial-sided forearm musculature is typically absent or

hypoplastic, contributing to a persistent radial deviation force that drives progressive deformity if uncorrected.

Functional limitations in RLD arise primarily from thumb dysfunction, wrist deviation and instability, forearm shortening, and reduced grip strength, which collectively impair fine motor tasks, reach distance, and upper extremity leverage [47]. Without correction, the hand remains in persistent radial deviation, which can progressively impair independence in activities of daily living and bimanual tasks and may necessitate compensatory strategies over time.

Systemic Findings Warranting Evaluation

Several clinical features should prompt systematic evaluation for associated syndromes: bilateral RLD, an absent or near-absent thumb alongside radial aplasia, a cardiac murmur or structural cardiac finding, thrombocytopenia or an abnormal complete blood count, renal anomalies on imaging, vertebral or anal abnormalities, or a family history consistent with autosomal dominant inheritance. The presence of any of these features substantially increases the likelihood of an underlying syndromic diagnosis and should prompt a targeted evaluation before operative planning [2,3,6].

Diagnostic evaluation

Evaluation of patients with RLD requires concurrent assessment of the limb deformity and systematic screening for associated systemic anomalies. Treatment planning should incorporate findings from both domains before operative intervention is undertaken [6].

Limb Assessment

Physical examination should characterize the degree of radial wrist deviation, assess active and passive wrist range of motion in all planes, document elbow range of motion, and evaluate thumb function using the Blauth classification to guide decisions regarding reconstruction and pollicization. Radiographs of the forearm, wrist, and hand, including elbow views when indicated, are essential for Bayne-Klug classification, evaluation of carpal anatomy, and assessment of ulnar morphology and growth plate integrity [3,48].

Systemic Screening

A complete blood count with a platelet count should be obtained in all patients, as thrombocytopenia may indicate TAR syndrome or Fanconi anemia. Echocardiography should be performed when Holt-Oram syndrome or VACTERL association is suspected on the basis of clinical features. Renal ultrasound is warranted when VACTERL association or other conditions with renal involvement are in the differential diagnosis. Vertebral imaging may be appropriate in complex or bilateral cases [2,3,6]. DEB chromosome breakage testing should be considered in patients with radial ray anomalies and clinical features suggestive of Fanconi anemia, including abnormal pigmentation, short stature, microcephaly, or a suggestive family history, as well as preoperatively in patients with unexplained cytopenias [3,25,26].

Prenatal Detection

Prenatal ultrasound is the primary modality for initial detection, with generally higher sensitivity for proximal or severe anomalies than for milder phenotypes [49]. Systematic evaluation of the metacarpal bone plane during fetal ultrasonography has been proposed to improve the detection of forearm and hand deformities [50]. When a radial ray anomaly is detected prenatally, genomic sequencing is recommended, particularly in bilateral or syndromic presentations [51].

Genetic Evaluation

Genetic evaluation, including chromosomal microarray and whole-exome or whole-genome sequencing, is indicated when RLD is bilateral, when associated anomalies are present, or when a specific syndrome is suspected. Genetic counseling should accompany testing to address recurrence risk and prognosis. For prenatal presentations, chorionic villus sampling or amniocentesis with genomic sequencing should be offered; genome sequencing has achieved high molecular diagnostic yields in fetuses with suspected genetic skeletal disorders, although evidence specific to isolated radial ray anomalies is limited [28,29].

Nonoperative management

Nonoperative management is the initial approach for all patients with RLD and remains appropriate across the lifespan for patients with mild deformity, significant comorbidities, or a family preference for nonoperative care. Goals include maintaining or improving passive wrist range of motion, preventing progressive soft tissue contracture, optimizing upper extremity function, and providing education and psychosocial support to parents and families [6]. Stretching and serial casting of the radial-sided contracted soft tissues are initiated early in infancy, typically within the first weeks of life, to elongate radial wrist

flexors and improve tissue compliance before any surgical intervention. Static and dynamic splinting between stretching sessions helps maintain positional gains [6]. In more severe cases, preliminary soft tissue distraction using external fixation devices may be used to gradually correct the deformity before definitive surgical reconstruction.

Occupational therapy (OT) is widely regarded as central to nonoperative management and remains relevant whether or not surgery is pursued. OT promotes functional independence through adaptive strategies, environmental modification, and task training. In a systematic review of pediatric OT for children with disabilities, conservative approaches such as home programs, parent education, and coaching received strong recommendations for use in specific diagnoses; this evidence is indirect and not specific to RLD [52]. In a qualitative study of children and families following reconstruction for congenital hand differences, children frequently developed individualized approaches to tasks that provided functional equivalence to typical hand use, illustrating the role of therapy in adaptive skill formation [53].

Prosthetic and assistive devices play a supplementary role in nonoperative management, although adoption rates remain low. A qualitative study found that only approximately 6% of children in a congenital hand differences cohort used prostheses or assistive devices, such as special pencil grips or scissors [53]. However, emerging evidence suggests that therapy-directed prosthetic training, including training with low-cost three-dimensionally (3D) printed devices, can improve dexterity and promote cortical neuroplasticity in pediatric patients with congenital limb reductions [54]. Three-dimensional printing may expand access to assistive technology by enabling patient-specific device fabrication at a reduced cost [54].

Operative management

The decision to pursue surgical intervention in RLD is individualized and should account for the severity of the deformity (Bayne-Klug type), the degree of thumb dysfunction (Blauth type), the presence of associated comorbidities, elbow range of motion, family goals, and surgeon experience. No single technique has been established as universally superior; treatment must be tailored to each patient [6,44,55].

Surgical Timing

Surgical intervention for severe RLD (Bayne-Klug types III-IV) is generally undertaken in infancy or early childhood; however, the optimal age for surgery and the relative merits of staged versus single-stage correction have not been established by comparative evidence. Preliminary soft tissue distraction is increasingly performed before definitive centralization or radialization to reduce contracture, decrease tension on the distal ulnar growth plate, and improve the surgical field [56,57].

Centralization

Centralization involves seating the carpus centrally on the distal ulna, classically with resection of one or more carpal bones to accommodate the ulnar head, with Kirschner wire fixation to maintain alignment; technical variations that avoid or minimize carpal resection have also been described [44,58]. Historically regarded as the standard surgical intervention for severe RLD, centralization has been shown to achieve substantial initial correction of wrist deviation [44,59]. Long-term experience has, however, identified concerns, including wrist stiffness attributable to carpal bone resection, injury to the distal ulnar physis from compressive forces, deformity recurrence from persistent muscular imbalance, and forearm shortening [44,55]. In the only randomized controlled trial identified, a small pilot trial of 17 affected limbs (9 centralization, 8 radialization) with 24-month follow-up, clinical forearm length was significantly shorter after centralization than after radialization (centralization 9.97 cm vs radialization 11.39 cm; $P = 0.03$) [60]. These preliminary findings, from a pilot trial for which no a priori sample size calculation was performed, require confirmation in adequately powered trials.

Radialization

In radialization, the hand is positioned on the ulnar border of the forearm, and the radial wrist tendons are transferred ulnarly to rebalance the deforming forces that contribute to recurrence after centralization [55,60]. In the same pilot trial (Bayne-Klug types III-IV), radialization was associated with greater preservation of forearm length and a smaller residual hand-forearm angle at 24 months than centralization (clinical hand-forearm angle: centralization 32° vs. radialization 10°, $P = 0.017$; total angulation: centralization 55° vs. radialization 31°, $P = 0.028$), with deformity recurrence being more marked in the centralization group [60]. In a systematic review, radialization maintained better wrist active range of motion (approximately 46°) and ulnar length than centralization [55]; in a separate long-term series of 20 limbs (5- to 19-year follow-up), the median loss of hand-forearm angle correction was 9°, though secondary procedures were sometimes required to maintain alignment [61].

Ulnarization

Ulnarization transfers the carpus onto the ulnar side of the distal ulna while aiming to preserve the ulnar

head and physis, and has been proposed to reduce physeal injury and growth disturbance associated with carpal-resection centralization. In a single case series, 22 radial club hands in 17 patients treated with a modified (third-generation) ulnarization achieved a mean hand-forearm angle correction of 68.5° from a preoperative mean of 76.2°; complications included wound problems, one deep wound infection, and one hand with no ulnar growth at one-year follow-up [48]. The authors emphasize that longer-term follow-up is required; these single-series results describe the procedure but do not establish superiority over centralization or radialization [48].

Soft Tissue Distraction

Preliminary soft tissue distraction using external fixators or serial casting provides gradual elongation of contracted radial-sided soft tissues before definitive reconstruction. In one series of 13 patients, distraction with articulated mini-rail fixators followed by centralization reduced the mean residual hand-forearm angulation to less than 12° [56]. Distraction carries device-related complications, and available evidence supports its use as a preparatory adjunct to centralization or radialization rather than as a standalone corrective procedure [62,63].

Vascularized Metatarsophalangeal Joint Transfer (Vilkki Procedure)

Introduced in 1987, the Vilkki procedure involves the free vascularized transfer of the second metatarsophalangeal (MTP) joint to reconstruct the absent radial column with biologically active tissue capable of continued growth [64]. A systematic review and meta-analysis found that MTP joint transfer yielded the highest reported active wrist range of motion of any surgical technique (approximately 83°), though with a worse final hand-forearm angle than centralization or radialization [55]. Long-term follow-up confirms that MTP joint transfer maintains greater wrist range of motion than radialization, although mild recurrence of radial deviation occurs during adolescence because the transferred physis does not fully match distal ulnar growth [64,65]. Secondary wrist procedures are more commonly required following MTP transfer than after radialization [65].

Emerging Techniques

Newer reconstructive approaches, such as distal ulnar bifurcation arthroplasty, have been described in the recent literature [66]. In this procedure, the distal ulna is bifurcated to seat and stabilize the carpus, combined with pollicization for a hypoplastic or absent thumb and, when the ulna is markedly bowed, corrective osteotomy [66]. In a single-center series of 11 children (15 forearms) with Bayne-Klug type III or IV deficiency who underwent surgery at a mean age of 55.5 months, the mean hand-forearm angle correction was 80.2°, active wrist motion averaged approximately 87.5°, and ulnar growth averaged 6.7 mm per year at a mean follow-up of 42.2 months; two forearms developed pin-tract infections that resolved with dressing changes and antibiotics, and no major complications or revisions were reported [66]. These preliminary findings come from a small case series with follow-up short of skeletal maturity and require confirmation [66]. Vascularized proximal fibular epiphyseal transfer has been explored as an experimental option for distal radius reconstruction in children; a systematic review characterized it as technically demanding and associated with a substantial complication burden, and its role relative to established procedures remains unclear [67].

Pollicization

For severe thumb deficiency - Blauth types IIIB, IV, and V - reconstruction of the native thumb is generally not feasible, and pollicization of the index finger is the preferred reconstructive option. As noted above, an international survey showed strong surgeon preference for pollicization in types IIIB and IV, reflecting practice preference rather than comparative outcome evidence [45]. The procedure repositions the index ray into the thumb position and reconstructs opposition; it is commonly coordinated with wrist-correction procedures [44,45]. Pollicization is among the more functionally consequential interventions in severe RLD, although comparative long-term outcome data remain limited [44].

Surgical outcomes and complications

Direct comparisons across surgical techniques are limited by heterogeneous patient populations, variable inclusion criteria, inconsistent outcome measures, and short follow-up periods in several series. The only randomized trial identified, a small pilot study, compared radialization with centralization [60]; all other data derive from retrospective case series or systematic reviews thereof.

Deformity recurrence is the predominant concern across all operative techniques and is driven by persistent muscular imbalance, radial soft tissue contracture, and ongoing asymmetric growth [61,62]. Correction under soft tissue tension also risks circulatory impairment of the hand as well as recurrence of radial deformity; tension-free correction (for example, by lunate excision or ulnar shortening) or gradual correction with external fixation in cases with severe radial deviation or a short forearm has been recommended to reduce these risks [1]. Centralization carries additional risks of wrist stiffness from carpal

bone resection and injury to the distal ulnar physis, which can impair forearm growth [55,60,62]. Nonsurgically treated patients retained greater wrist range of motion than most surgically treated patients in the systematic review by Murphy et al. [55], underscoring that the goal of surgery is long-term deformity correction and functional improvement rather than maximizing range of motion. Isolated soft tissue release with a bilobed flap, without centralization, offers a middle course: at a mean of 9.2 years it preserved a 73° wrist arc without physeal arrest but corrected less deformity (mean resting radial deviation 64°), and it was the option most often preferred for type III or IV deficiency in an international survey (42%) [45,55,68]. Evidence quality throughout the RLD surgical literature is limited; most available studies are retrospective with small sample sizes, heterogeneous populations, and inconsistent outcome measures, and a systematic review rated the evidence as low or very low quality using the Grading of Recommendations, Assessment, Development and Evaluation (GRADE) criteria [55]. Reported outcomes by technique are summarized in Table *1*.

Technique	Hand-forearm angle	Active wrist ROM	Key trade-off	References
Nonoperative	84° (worsening)	61°	Better active wrist ROM than most surgically treated groups; progressive deformity without correction	[55]
Centralization	Substantial initial correction	Lowest among surgical options	Large correction from a more severe baseline; risk of stiffness, physeal injury, and recurrence	[44,55,59,60]
Radialization	Median 9° loss of correction at 5-19 years	~46°	Longer forearm and less recurrence than centralization in one pilot trial; recurrence common in other series	[55,60,61,63,65]
Soft tissue release with bilobed flap	~64°	~73°	Preserves physis and ROM; less deformity correction	[55,68]
MTP joint transfer (Vilkki)	Poorer than centralization or radialization	~83° (highest reported)	Greatest reported ROM; secondary procedures more common; lower satisfaction with appearance	[55,64,65]
Fibular epiphyseal transfer	Experimental	Limited data	Growth potential; substantial complication burden	[67]
Soft tissue distraction (preparatory)	<12° residual after centralization in one 13-patient series	Variable	Facilitates realignment; did not prevent recurrence in a comparative series; frequent pin-related reoperations	[56,57,62,63]

TABLE 1: Comparative outcomes across reported surgical techniques for radial longitudinal deficiency.

This table is original, created by the authors from published data in the cited sources. Angles are in degrees; direct comparison is limited by heterogeneous patient populations and outcome measures.

ROM, range of motion; MTP, metatarsophalangeal

Psychosocial impact

RLD and congenital upper limb differences carry meaningful psychosocial consequences for affected children and their families. Direct psychosocial research specific to RLD is scarce; the evidence summarized below derives from broader populations - children and adolescents with congenital limb reduction deficiency, congenital upper limb differences, and prosthesis users - rather than from RLD-specific cohorts, and should be interpreted as indirect. These findings may not fully capture the experiences specific to RLD phenotypes and treatment pathways.

Children with visible upper limb differences may experience difficulties with self-esteem, body image, and social integration, particularly during peer-intensive developmental periods [53]. In a Swedish study of 62 children with upper limb reduction deficiency who had myoelectric prostheses, overall psychosocial adjustment was similar to population norms, although withdrawn behavior was more common, girls had lower social competence, and children who did not use their prosthesis had more delinquent behavior problems than full-time users [69]. Health-related quality of life studies indicate that while many affected children report overall positive mental health, unwanted attention related to appearance can negatively

affect emotional functioning and social participation, and girls with longitudinal deficiencies reported lower quality of life than girls with other forms of limb deficiency [70]. Parents describe an ambivalent role as decision-makers for their child, with anxiety and uncertainty around early treatment choices and limited emotional support [71].

The psychosocial impact of RLD changes across the lifespan. In childhood, parents and clinical teams largely shape treatment decisions. During adolescence, affected individuals increasingly integrate these decisions into their developing sense of identity and autonomy [71,72]. Adolescents with congenital limb reduction deficiencies have reported that treatments received during childhood shaped their self-confidence, while also raising questions about future functioning and independence [72].

Adolescents with congenital limb reduction deficiency described childhood treatment as creating opportunities and building the skills and confidence to choose their own path [72]. These responses underscore the importance of incorporating patient and family perspectives into treatment planning throughout the developmental arc. In the same qualitative study, adolescents described camps and group activities as fostering a sense of belonging [72]. In the broader pediatric disability literature, coaching and family-centered OT approaches are supported by systematic review evidence [52].

Limitations

There are several limitations to this review. Because of its nonsystematic design, the selection of sources is subject to selection and publication bias. Since RLD is uncommon, the available clinical evidence consists largely of small retrospective series with heterogeneous designs, classification systems, and outcome measures, and patient-reported outcome measures, such as the Disabilities of the Arm, Shoulder and Hand (DASH) questionnaire, have been inconsistently reported. Limited long-term follow-up in many series may not capture late recurrence of deformity or longer-term functional outcomes. Formal risk-of-bias assessment and quantitative pooling were not performed because of the narrative design and the heterogeneity of the available studies.

Controversies and future directions

Optimal Surgical Timing and Technique

The optimal timing of surgical intervention in severe RLD remains incompletely resolved, and the comparative benefit of staged versus single-stage correction has not been established by comparative evidence; preliminary soft tissue distraction is widely used, but whether it reduces long-term recurrence is unresolved [55-57,62,63]. No single surgical technique has demonstrated superiority across all outcome dimensions. Centralization offers reliable initial correction but carries risks of recurrence and growth disturbance [55,60,62]. In one small randomized pilot trial, radialization preserved forearm length and limited recurrence better than centralization at 24 months [60], but recurrence after radialization has been frequent in other series [63,65]. MTP joint transfer provides the greatest reported wrist range of motion but requires complex microsurgery and is associated with a greater need for secondary procedures [55,64,65]. Newer procedures continue to be described, but they currently lack accessible long-term comparative data. Determining which technique best serves a given patient requires individualized assessment of deformity severity, elbow function, thumb status, associated comorbidities, surgeon expertise, and family goals.

Standardized Outcomes and Registry-Based Research

A major barrier to advancing the evidence base in RLD is the absence of standardized outcome reporting. Future studies should consistently report hand-forearm angle, active wrist range of motion, grip strength, patient-reported outcomes such as the DASH questionnaire [73] or Patient-Reported Outcomes Measurement Information System (PROMIS) measures [74] where validated for the patient's age, validated pediatric functional measures, cosmetic satisfaction, complication rates, revision rates, and psychosocial outcomes alongside radiographic data. Because the limb changes throughout growth and the final result is apparent only at skeletal maturity, serial objective documentation, including radiographs and standardized functional measures, is important through skeletal maturity [55]. Pediatric PROMIS upper extremity measures have shown good construct validity in children with congenital hand differences [75] and strong convergent validity with the Pediatric Outcomes Data Collection Instrument (PODCI) in a multicenter registry cohort of 359 children with congenital upper limb anomalies [76], and they are quicker to complete [75,76]. Although these cohorts included a range of congenital diagnoses rather than RLD specifically, the findings support the use of pediatric PROMIS measures for patient-reported functional outcomes. Treatment success must not be based on radiographic correction alone; outcomes that matter most to patients and families-functional independence, participation in daily activities, and psychosocial well-being-should be central to the design of future trials and longitudinal follow-up studies [6]. In one series of children with RLD, hand-forearm angle was not associated with measures of activity or participation [47]. Registry platforms such as the CoULD registry provide a framework for comparing outcomes across institutions and geographic regions in a condition too rare for most single-center studies to achieve adequate statistical power [12]. Multicenter registry-based studies represent a research priority for the field [12].

Advances in Prenatal Molecular Diagnosis

Prenatal genome sequencing is improving molecular diagnosis of fetal skeletal disorders, but evidence specific to radial ray anomalies is limited [28]. Studies that link prenatal genetic findings with postnatal phenotype, associated anomalies, and treatment in RLD would directly improve prenatal counseling.

Emerging Technologies

Three-dimensional printing may allow low-cost, patient-specific orthoses and assistive devices, but evidence in children with limb differences is preliminary and does not include RLD [54].

Gene Editing

As discussed above, gene editing approaches to RLD remain preclinical, and the genetic heterogeneity of RLD, the availability of effective postnatal treatments, and the technical, safety, and ethical barriers to in utero gene modification argue against near-term clinical application [30-33]. Meaningful advances in the care of patients with RLD are more likely to arise in the foreseeable future from improved genetic diagnosis, multidisciplinary prenatal counseling, standardized surgical planning, better-defined rehabilitation protocols, and sustained long-term outcomes research than from direct genetic correction.

Conclusions

RLD is a rare congenital upper extremity malformation that exists on a broad spectrum, from isolated thumb hypoplasia to complete radial aplasia with severe wrist deviation and significant functional impairment. The condition may occur as an isolated musculoskeletal anomaly or as part of syndromic presentations, including Holt-Oram syndrome, Fanconi anemia, TAR syndrome, and VACTERL association, each carrying independent systemic implications that extend well beyond the orthopedic deformity. Advances in embryology and molecular genetics have improved understanding of the developmental pathways responsible for RLD, while modern classification systems, particularly the OMT classification and the Bayne-Klug and Blauth systems, have enhanced diagnostic consistency and surgical planning. Surgical techniques have evolved from historical carpal-resection centralization toward growth-preserving approaches such as radialization and vascularized joint transfer, with newer procedures continuing to be investigated; no single technique has been shown to be universally superior, and comparative long-term evidence remains limited. Psychosocial considerations represent an essential and often underaddressed dimension of care, requiring attention alongside physical and functional outcomes throughout childhood and adolescence.

This review supports a multidisciplinary, patient-centered approach to RLD management. Early identification of associated syndromes and systemic comorbidities is essential to guide surveillance, surgical planning, and long-term care. Genetic counseling and appropriate diagnostic testing should be offered, particularly in bilateral or syndromic presentations, and DEB testing for Fanconi anemia should be considered whenever clinical features or unexplained cytopenias raise concern. Thumb function must be assessed independently using the Blauth classification, as the decision between reconstruction and pollicization represents one of the most consequential treatment choices in severe RLD. Treatment decisions should prioritize functional outcomes and quality of life over radiographic correction alone. Family-centered care, patient involvement in decision-making when developmentally appropriate, and sustained psychosocial support throughout childhood and adolescence are integral to successful long-term outcomes. Future research should prioritize multicenter, registry-based studies to characterize long-term outcomes across diverse patient populations and surgical techniques. Standardized outcome measures encompassing functional performance, participation, patient-reported outcomes, and psychosocial well-being, alongside radiographic data, are needed to enable meaningful comparisons across approaches. Additional investigation is warranted for emerging reconstructive techniques, growth-preserving procedures, and 3D-printed assistive technologies. Occupational therapy interventions and psychosocial adaptation specific to individuals with RLD, rather than to the broader population with congenital upper limb differences, represent important gaps in the current literature. Continued advances in prenatal genomic sequencing and multidisciplinary counseling will further improve early identification, syndrome characterization, and individualized treatment planning in this complex congenital condition.

Additional Information

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All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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References

1. Takagi T, Seki A, Takayama S, Watanabe M: Current concepts in radial club hand . Open Orthop J. 2017, 11:369-77. 10.2174/1874325001711010369
2. Elmakky A, Stanghellini I, Landi A, Percesepe A: Role of genetic factors in the pathogenesis of radial deficiencies in humans. Curr Genomics. 2015, 16:264-78. 10.2174/1389202916666150528000412
3. Forman M, Canizares MF, Bohn D, et al.: Association of radial longitudinal deficiency and thumb hypoplasia: an update using the CoULD registry. J Bone Joint Surg Am. 2020, 102:1815-22. 10.2106/JBJS.20.00281
4. Syvänen J, Raitio A, Helenius I, Löyttyniemi E, Lahesmaa-Korpinen AM, Gissler M, Nietosvaara Y: Prevalence and risk factors of radial ray deficiencies: a population-based case-control study . Am J Med Genet A. 2021, 185:759-65. 10.1002/ajmg.a.62033
5. Koskimies E, Lindfors N, Gissler M, Peltonen J, Nietosvaara Y: Congenital upper limb deficiencies and associated malformations in Finland: a population-based study. J Hand Surg Am. 2011, 36:1058-65. 10.1016/j.jhsa.2011.03.015
6. Wall LB, Ezaki M, Oishi SN: Management of congenital radial longitudinal deficiency: controversies and current concepts. Plast Reconstr Surg. 2013, 132:122-8. 10.1097/PRS.0b013e318290fca5
7. Goldfarb CA, Wall L, Manske PR: Radial longitudinal deficiency: the incidence of associated medical and musculoskeletal conditions. J Hand Surg Am. 2006, 31:1176-82. 10.1016/j.jhsa.2006.05.012
8. Halverson SJ, Takayama S, Ochi K, Seki A, Wall LB, Goldfarb CA: Radial longitudinal deficiency: severity differences between U.S. and Japanese cohorts. J Hand Surg Am. 2020, 45:196-202. 10.1016/j.jhsa.2019.12.004
9. Goldberg MJ, Meyn M: The radial clubhand. Orthop Clin North Am. 1976, 7:341-59. 10.1016/S0030-5898(20)30198-X
10. Pakkasjärvi N, Koskimies E, Ritvanen A, Nietosvaara Y, Mäkitie O: Characteristics and associated anomalies in radial ray deficiencies in Finland - a population-based study. Am J Med Genet A. 2013, 161:261-7. 10.1002/ajmg.a.35707
11. Giele H, Giele C, Bower C, Allison M: The incidence and epidemiology of congenital upper limb anomalies: a total population study. J Hand Surg Am. 2001, 26:628-34. 10.1053/jhsu.2001.26121
12. Vuillermin C, Canizares MF, Bauer AS, Miller PE, Goldfarb CA: Congenital Upper Limb Differences Registry (CoULD): registry inclusion effect. J Hand Surg Am. 2021, 46:515.e1-11. 10.1016/j.jhsa.2020.11.006
13. Goldfarb CA, Shaw N, Steffen JA, Wall LB: The prevalence of congenital hand and upper extremity anomalies based upon the New York Congenital Malformations Registry. J Pediatr Orthop. 2017, 37:144-8. 10.1097/BPO.0000000000000748
14. O'Keefe D, Kennedy J, McCombe D, Coombs C, Hui L, Wilks D, Halliday J: Pre-natal and post-natal diagnosis of congenital upper limb differences: the first 3 years of the Australian Hand Difference Register. J Paediatr Child Health. 2022, 58:122-8. 10.1111/jpc.15673
15. Ogino T: Clinical features and teratogenic mechanisms of congenital absence of digits . Dev Growth Differ. 2007, 49:523-31. 10.1111/j.1440-169X.2007.00939.x
16. Little KJ, Cornwall R: Congenital anomalies of the hand—principles of management . Orthop Clin North Am. 2016, 47:153-68. 10.1016/j.ocl.2015.08.015
17. Lam WL, Oh JD, Johnson EJ, Poyatos Pertinez S, Stephens C, Davey MG: Experimental evidence that preaxial polydactyly and forearm radial deficiencies may share a common developmental origin. J Hand Surg Eur Vol. 2019, 44:43-50. 10.1177/1753193418762959
18. Stricker S, Mundlos S: Mechanisms of digit formation: human malformation syndromes tell the story . Dev Dyn. 2011, 240:990-1004. 10.1002/dvdy.22565
19. Vergult S, Hoogeboom AJ, Bijlsma EK, et al.: Complex genetics of radial ray deficiencies: screening of a cohort of 54 patients. Genet Med. 2013, 15:195-202. 10.1038/gim.2012.120
20. Al-Qattan MM: WNT pathways and upper limb anomalies . J Hand Surg Eur Vol. 2011, 36:9-22. 10.1177/1753193410380502
21. Guasto A, Cormier-Daire V: Signaling pathways in bone development and their related skeletal dysplasia . Int J Mol Sci. 2021, 22:10.3390/ijms22094321
22. Restelli M, Lopardo T, Lo Iacono N, et al.: DLX5, FGF8 and the Pin1 isomerase control ΔNp63α protein stability during limb development: a regulatory loop at the basis of the SHFM and EEC congenital malformations. Hum Mol Genet. 2014, 23:3830-42. 10.1093/hmg/ddu096
23. Meester JA, Sukalo M, Schröder KC, et al.: Elucidating the genetic architecture of Adams-Oliver syndrome in

a large European cohort. Hum Mutat. 2018, 39:1246-61. 10.1002/humu.23567
24. Stittrich AB, Lehman A, Bodian DL, et al.: Mutations in NOTCH1 cause Adams-Oliver syndrome. Am J Hum Genet. 2014, 95:275-84. 10.1016/j.ajhg.2014.07.011
25. Webb ML, Rosen H, Taghinia A, McCarty ER, Cerrato F, Upton J, Labow BI: Incidence of Fanconi anemia in children with congenital thumb anomalies referred for diepoxybutane testing. J Hand Surg Am. 2011, 36:1052-7. 10.1016/j.jhsa.2011.02.018
26. Wilks DJ, Kay SP, Bourke G: Fanconi's anaemia and unilateral thumb polydactyly - don't miss it. J Plast Reconstr Aesthet Surg. 2012, 65:1083-6. 10.1016/j.bjps.2012.02.015
27. Petit F, Boussion S: Thrombocytopenia Absent Radius Syndrome. Adam MP, Bick S, Mirzaa GM, et al. (ed): University of Washington, Seattle, WA; 2023.
28. Lindelöf H, Hammarsjö A, Voss U, et al.: Genome sequencing in a cohort of 32 fetuses with genetic skeletal disorders. Eur J Hum Genet. 2025, 33:1474-83. 10.1038/s41431-025-01886-x
29. Gandhi M, Rac M, McKinney J: Radial ray malformation. Am J Obstet Gynecol. 2019, 221:B16-8. 10.1016/j.ajog.2019.09.024
30. O'Connell AE, Guseh S, Lapteva L, et al.: Gene and stem cell therapies for fetal care: a review . JAMA Pediatr. 2020, 174:985-91. 10.1001/jamapediatrics.2020.1519
31. Mattar CN, Chan JK, Choolani M: Gene modification therapies for hereditary diseases in the fetus . Prenat Diagn. 2023, 43:674-86. 10.1002/pd.6347
32. Bose SK, Kennedy K, Peranteau WH: Foetal genome editing. Curr Opin Obstet Gynecol. 2023, 35:134-9. 10.1097/GCO.0000000000000854
33. Ricciardi AS, Bahal R, Farrelly JS, et al.: In utero nanoparticle delivery for site-specific genome editing. Nat Commun. 2018, 9:2481. 10.1038/s41467-018-04894-2
34. Swanson AB: A classification for congenital limb malformations. J Hand Surg Am. 1976, 1:8-22. 10.1016/s0363-5023(76)80021-4
35. Oberg KC: Classification of congenital upper limb anomalies: towards improved communication, diagnosis, and discovery. J Hand Surg Eur Vol. 2019, 44:4-14. 10.1177/1753193418801280
36. Tonkin MA, Tolerton SK, Quick TJ, Harvey I, Lawson RD, Smith NC, Oberg KC: Classification of congenital anomalies of the hand and upper limb: development and assessment of a new system. J Hand Surg Am. 2013, 38:1845-53. 10.1016/j.jhsa.2013.03.019
37. Tonkin MA: Classification of congenital anomalies of the hand and upper limb . J Hand Surg Eur Vol. 2017, 42:448-56. 10.1177/1753193417690965
38. Goldfarb CA, Ezaki M, Wall LB, Lam WL, Oberg KC: The Oberg-Manske-Tonkin (OMT) classification of congenital upper extremities: update for 2020. J Hand Surg Am. 2020, 45:542-7. 10.1016/j.jhsa.2020.01.002
39. Manske PR, Oberg KC: Classification and developmental biology of congenital anomalies of the hand and upper extremity. J Bone Joint Surg Am. 2009, 91:3-18. 10.2106/JBJS.I.00008
40. Bayne LG, Klug MS: Long-term review of the surgical treatment of radial deficiencies . J Hand Surg Am. 1987, 12:169-79. 10.1016/s0363-5023(87)80267-8
41. Blauth W: Der hypoplastische Daumen [The hypoplastic thumb] . Arch Orthop Unfallchir. 1967, 62:225-46. 10.1007/BF00416751
42. Manske PR, McCarroll HR Jr, James M: Type III-A hypoplastic thumb. J Hand Surg Am. 1995, 20:246-53. 10.1016/S0363-5023(05)80018-8
43. Tonkin MA: On the classification of congenital thumb hypoplasia . J Hand Surg Eur Vol. 2014, 39:948-55. 10.1177/1753193413516246
44. Colen DL, Lin IC, Levin LS, Chang B: Radial longitudinal deficiency: recent developments, controversies, and an evidence-based guide to treatment. J Hand Surg Am. 2017, 42:546-63. 10.1016/j.jhsa.2017.04.012
45. Wall LB, Kim DJ, Cogsil T, Goldfarb CA: Treatment of radial longitudinal deficiency: an international survey. J Hand Surg Am. 2021, 46:241.e1-11. 10.1016/j.jhsa.2020.07.018
46. Lowry RB, Bedard T, Kiefer GN, Sass KR: Views on the Oberg-Manske-Tonkin classification system for congenital anomalies of the hand and upper limb. J Hand Surg Am. 2017, 42:378-81. 10.1016/j.jhsa.2017.02.018
47. Ekblom AG, Dahlin LB, Rosberg HE, Wiig M, Werner M, Arner M: Hand function in children with radial longitudinal deficiency. BMC Musculoskelet Disord. 2013, 14:116. 10.1186/1471-2474-14-116
48. Deszczynski JM, Albrewczynski T, Shannon C, Paley D: Radial club hand treated by Paley ulnarization generation 3: is this the new centralization?. Children (Basel). 2021, 8:10.3390/children8070562
49. Piper SL, Dicke JM, Wall LB, Shen TS, Goldfarb CA: Prenatal detection of upper limb differences with obstetric ultrasound. J Hand Surg Am. 2015, 40:1310-7.e3. 10.1016/j.jhsa.2015.04.013
50. Zhou L, Lv M, Zeng M, et al.: Metacarpal bone plane examination by ultrasonography for the diagnosis of fetal forearm and hand deformity. Sci Rep. 2017, 7:42161. 10.1038/srep42161
51. Arduç A, van Dijk SJ, Ten Cate FJ, et al.: Phenotype-to-genotype description of prenatal suspected and postnatal discovered upper limb anomalies: a retrospective cohort study. Prenat Diagn. 2025, 45:3-14. 10.1002/pd.6714
52. Novak I, Honan I: Effectiveness of paediatric occupational therapy for children with disabilities: a systematic review. Aust Occup Ther J. 2019, 66:258-73. 10.1111/1440-1630.12573
53. Kelley BP, Franzblau LE, Chung KC, Carlozzi N, Waljee JF: Hand function and appearance following reconstruction for congenital hand differences: a qualitative analysis of children and parents. Plast Reconstr Surg. 2016, 138:73-81e. 10.1097/PRS.0000000000002286
54. Borrell JA, Karumattu Manattu A, Copeland C, et al.: Prosthetic home intervention induces cortical plasticity in paediatrics with congenital limb reduction. Brain Commun. 2024, 6:fcae044. 10.1093/braincomms/fcae044
55. Murphy GR, Logan MP, Smith G, Sivakumar B, Smith P: Correction of "wrist" deformity in radial dysplasia: a systematic review and meta-analysis. J Bone Joint Surg Am. 2017, 99:2120-6. 10.2106/JBJS.17.00164
56. Romana C, Ciais G, Fitoussi F: Treatment of severe radial club hand by distraction using an articulated mini-rail fixator and transfixing pins. Orthop Traumatol Surg Res. 2015, 101:495-500. 10.1016/j.otsr.2015.02.009
57. Pfister G, Le Hanneur M, Bachy M, Fitoussi F: Radial club hand treated with soft-tissue distraction and

subsequent pin stabilization: mid- to long-term results. J Hand Surg Eur Vol. 2020, 45:729-36. 10.1177/1753193420916694

58. Watson HK, Beebe RD, Cruz NI: A centralization procedure for radial clubhand . J Hand Surg Am. 1984, 9:541-7. 10.1016/s0363-5023(84)80107-0
59. Lamb DW: Radial club hand: a continuing study of sixty-eight patients with one hundred and seventeen club hands. J Bone Joint Surg Am. 1977, 59:1-13. 10.2106/00004623-197759010-00001
60. Mittal S, Garg B, Mehta N, Kumar V, Kotwal P: Randomized trial comparing preliminary results of radialization and centralization procedures in Bayne types 3 and 4 radial longitudinal deficiency. J Pediatr Orthop. 2020, 40:509-14. 10.1097/BPO.0000000000001606
61. Bhat AK, Narayanakurup JK, Acharya AM, Kumar B: Outcomes of radialization for radial longitudinal deficiency: 20 limbs with minimum 5-year follow-up. J Hand Surg Eur Vol. 2019, 44:304-9. 10.1177/1753193418788935
62. Manske MC, Wall LB, Steffen JA, Goldfarb CA: The effect of soft tissue distraction on deformity recurrence after centralization for radial longitudinal deficiency. J Hand Surg Am. 2014, 39:895-901. 10.1016/j.jhsa.2014.01.015
63. Dana C, Aurégan JC, Salon A, Guéro S, Glorion C, Pannier S: Recurrence of radial bowing after soft tissue distraction and subsequent radialization for radial longitudinal deficiency. J Hand Surg Am. 2012, 37:2082-7. 10.1016/j.jhsa.2012.07.018
64. Vilkki SK, Paavilainen P: Vascularized second metatarsophalangeal joint transfer for radial deficiency - an update. J Hand Surg Eur Vol. 2018, 43:907-18. 10.1177/1753193418793597
65. Kämppä N, Grahn P, Paavilainen P, Nietosvaara Y, Jokihaara J: Radial longitudinal deficiency: long-term outcomes of radialization and vascularized metatarsophalangeal joint transfer. J Hand Surg Eur Vol. 2026, 51:472-9. 10.1177/17531934251391119
66. Jia YC, Zhao HY, Wu TY, Xu J, Kang QL: Distal ulnar bifurcation arthroplasty in the treatment of Bayne and Klug types 3 and 4 radial club hands: preliminary outcomes. Plast Reconstr Surg. 2023, 152:583-92. 10.1097/PRS.0000000000010396
67. Aldekhayel S, Govshievich A, Neel OF, Luc M: Vascularized proximal fibula epiphyseal transfer for distal radius reconstruction in children: a systematic review. Microsurgery. 2016, 36:705-11. 10.1002/micr.22521
68. Vuillermin C, Wall L, Mills J, Wheeler L, Rose R, Ezaki M, Oishi S: Soft tissue release and bilobed flap for severe radial longitudinal deficiency. J Hand Surg Am. 2015, 40:894-9. 10.1016/j.jhsa.2015.01.004
69. Hermansson L, Eliasson AC, Engström I: Psychosocial adjustment in Swedish children with upper-limb reduction deficiency and a myoelectric prosthetic hand. Acta Paediatr. 2005, 94:479-88. 10.1111/j.1651-2227.2005.tb01921.x
70. Ylimäinen K, Nachemson A, Sommerstein K, Stockselius A, Norling Hermansson L: Health-related quality of life in Swedish children and adolescents with limb reduction deficiency. Acta Paediatr. 2010, 99:1550-5. 10.1111/j.1651-2227.2010.01855.x
71. Sjöberg L, Hermansson L, Lindner H, Fredriksson C: Swedish parents' experiences of their role in treatment for children with congenital limb reduction deficiency: decision-making and treatment support. Child Care Health Dev. 2020, 46:723-32. 10.1111/cch.12802
72. Sjöberg L, Hermansson L, Lindner H, Fredriksson C: Adolescents with congenital limb reduction deficiency: perceptions of treatment during childhood and its meaning for their current and future situation. Child Care Health Dev. 2022, 48:613-22. 10.1111/cch.12967
73. Hudak PL, Amadio PC, Bombardier C: Development of an upper extremity outcome measure: the DASH (disabilities of the arm, shoulder, and hand). Am J Ind Med. 1996, 29:602-8. 10.1002/(SICI)1097-0274(199606)29:6<602::AID-AJIM4>3.0.CO;2-L
74. Cella D, Riley W, Stone A, et al.: The Patient-Reported Outcomes Measurement Information System (PROMIS) developed and tested its first wave of adult self-reported health outcome item banks: 2005-2008. J Clin Epidemiol. 2010, 63:1179-94. 10.1016/j.jclinepi.2010.04.011
75. Waljee JF, Carlozzi N, Franzblau LE, Zhong L, Chung KC: Applying PROMIS to assess upper extremity function among children with congenital hand differences. Plast Reconstr Surg. 2015, 136:200-7e. 10.1097/PRS.0000000000001444
76. Wall LB, Vuillermin C, Miller PE, Bae DS, Goldfarb CA: Convergent validity of PODCI and PROMIS domains in congenital upper limb anomalies. J Hand Surg Am. 2020, 45:33-40. 10.1016/j.jhsa.2019.08.003